"Ex-Post" evaluation of the IAP network P6/23

"Advanced Research on Exotic Nuclei for Nuclear Physics and Nuclear Astrophysics"

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"The BriX network:
Belgian Research Initiative on eXotic nuclei"

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LIST OF ABBREVIATIONS

BDF: beta-delayed fission

BR1: Belgian Reactor nr. 1 at the SCK•CEN site (Belgium)

BriX: Belgian Research Initiative on eXotic nuclei

COULEX: Coulomb Excitation

CSNSM: Centre de Spectrocmétrie Nucléaire et de Spectrométrie de Masse (Orsay, France)

EURONS: Integrated Infrastructure Initiative for EUROpean Nuclear Structure research

FAIR: Facility for Anti-proton and Ion Research (GSI)

GANIL: Grand Accélérateur National d'Ions Lourds (Caen, France)

GELINA: Geel Electron LINear Accelerator (Geel, Belgium)

GSI: Gesellschaft für Schwerionenforschung (Darmstadt, Germany)

HIE-ISOLDE: High Intensity and high Energy ISOLDE (CERN, Switzerland)

IKP-Köln: Universität zu Köln (Köln, Germany)

IRMM: Institute for Reference Materials and Measurements (Geel, Belgium)

ISOLDE: CERN's Isotope Separator On-Line facility (CERN, Switzerland)

K.U.Leuven: Katholieke Universiteit Leuven (Belgium)

LISOL: Leuven Isotope Separator On-Line (Belgium)

MINIBALL: a germanium detector array consisting of segmented detectors.

MYRRHA: a Multipurpose hYbrid Research Reactor for High-end Applications at SCK•CEN

NSAC: Nuclear Science Advisory Committee (U.S.A.)

NuPECC: Nuclear Physics European Collaboration Committee

PALIS: PArasitic RI-beam by Laser Ionization Source

RIKEN RIBF: Radioactive Beam Factory at RIKEN (Japan)

SCK•CEN: Studiecentrum voor Kernenergie • Centre d'Etude de l'Energie Nucléaire (Belgium)

SPIG: Sextupole Ion Guide

SPIRAL-2: Système de Production d'Ions Radioactifs en Ligne (GANIL)

UGent: Universiteit Gent (Belgium)

ULB: Université Libre de Bruxelles (Belgium)

WP: work package

1. INTRODUCTION

1.1 Title and composition

The present IAP P6/23 network entitled:

"Advanced Research on Exotic Nuclei for Nuclear Physics and Nuclear Astrophysics"

represents a collaboration between research groups from the following Belgian universities and research institute:

- Katholieke Universiteit Leuven (K.U.Leuven)
  Instituut voor Kern- en Stralingsfysica
  (M. Huyse, G. Neyens, R. Raabe, N. Severijns, P. Van Duppen,)
- Université Libre de Bruxelles (ULB)
  Physique Nucléaire Théorique et Physique Mathématique
  (D. Baye, P. Descouvemont, P.H. Heenen, J.M. Sparenberg)
- Universiteit Gent (UGent)
  Theoretische fysica - Vakgroep Subatomaire en Stralingsfysica
  (K. Heyde, N. Jachowicz, C. Wagemans)
- Studiecentrum voor Kernenergie • Centre d'Etude de l'Energie Nucléaire (SCK•CEN)
  (H. Aït Abderrahim, J. Heyse, L. Popescu, P. Schuurmans, J. Wagemans)

and research groups from the following international research institutes and universities:

- Grand Accélérateur National d'Ions Lourds (GANIL – Caen, France)
- Gesellschaft für Schwerionenforschung (GSI – Darmstadt, Germany)
- Universität zu Köln (IKP – U.Köln, Germany)
- Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse (CSNSM – Orsay, France)

Very close contacts with research groups from the ISOLDE facility (CERN) are present but because of administrative restrictions from BELSPO the ISOLDE group was not allowed to be taken up as official international partner in the network.

The network has organized itself into the so-called **"Belgian Research Initiative on eXotic nuclei: BriX network"**. This network brings together most of the Belgian expertise in theoretical and experimental fundamental nuclear-physics research in the field of exotic radioactive nuclei. The choice of the name and logo of the network has been established using a voting procedure amongst all PhD students, post-docs and staff involved in the network. The networks website is a wiki-type page: http://iks32.fys.kuleuven.be/wiki/brix/index.php/Main_Page

1.2 Budget

The total budget for the network was 2.600.000 € that was divided amongst the partners in the following way:

K.U.Leuven:	1.250.000 €
ULB:	400.000 €
UGent:	450.000 €
SCK•CEN:	400.000 €

GANIL;	24.000 €
GSI:	24.000 €
IKP-Köln:	26.000 €
CSNSM:	26.000 €

1.3 Brief history of the network

Phase I (1987-1991): The production and acceleration of radioactive ion beams and their use in nuclear physics, nuclear astrophysics and solid state studies (UCL, ULB and K.U.Leuven)
The study of the excitation and ionization of multiply charged ions by electrons and photons
Phase II: Radioactive ion beams (addition to phase I) (UCL, ULB and K.U.Leuven)
Phase III (1992-1996): Radioactive ion beams (UCL, ULB and K.U.Leuven)
Phase IV (1997-2001): Production and use of radioactive nuclear beams in nuclear astrophysics and nuclear physics (UCL, ULB and K.U.Leuven)
Phase V (2002-2006): Exotic nuclei for nuclear physics and nuclear astrophysics (K.U.Leuven, UCL, ULB and UGent, EU: GANIL, GSI)

The IAP collaboration was started in 1987, with the partners from the UCL, K.U.Leuven, and ULB: i.e. accelerator physicists from the UCL Cyclotron Research Center (CRC), experimental nuclear physicists from the universities of Brussels (ULB), Leuven (K.U.Leuven) and Louvain-la-Neuve (UCL), theoretical nuclear physicists from the ULB-PNTPM and astrophysicists from ULB-IAA. The main theme of the network was "Production and Use of Radioactive Ion Beams" and was initially focused on studies of relevance for nuclear astrophysics. The production of an intense, post-accelerated ^{13}N beam represented a world premiere in 1990. The development and optimization of different target and ion-source systems, the construction of a dedicated accelerator and in-flight separator for the astrophysical measurements has resulted in a substantial increase of the variety, intensity and energy range of the beams. Parallel to this R&D activity for post-accelerated beams, new methods for the production of exotic nuclei using laser ionization and new detection systems were developed.
The use of the radioactive beams was originally motivated by nuclear astrophysics only: the measurement of the $^{13}N(p,\gamma)^{14}O$ reaction was a world premiere in 1991. In close connection to the above mentioned experimental activity, theoretical efforts were undertaken for the

development of multidimensional hydrodynamic modeling of the nova phenomenon, for the construction of a new data base of nuclear astrophysics reactions and for the development of theoretical approaches and extended numerical codes to describe the structure and reactivity of stable and unstable nuclei. Apart from the astrophysical activity, a strong nuclear physics motivation grew through for example studies of the halo nucleus ^{6}He.

Based on the achievements and the expertise acquired from the “Interuniversity Attraction Poles" network phases I to III and in line with the international situation (following e.g. the NuPECC Long Range Plan) the network continued to broaden its activities and its collaboration. An intensive program to post-accelerate and exploit the radioactive ion beams from the ISOLDE-CERN project was initiated and resulted in complementary activities (phase IV). The theory group of Gent (UGent) and two more nuclear physics groups from the K.U.Leuven were included in phase V as well as the international partners from GANIL (France), GSI (Germany) and ISOLDE-CERN, (Switzerland). Furthermore, more emphasis on the experimental and theoretical study of exotic nuclei was put in the network’s program and its objectives. In this way the new network embedded essentially all Belgian activities in the field of nuclear structure of exotic nuclei as well as nuclear astrophysics.

The present network (phase VI) involves experimental and complementary theoretical investigations in nuclear-structure and reaction studies using radioactive isotopes and furthermore explores the potential for fundamental research using the opportunities offered by the MYRRHA project, a high-intensity proton accelerator coupled to a subcritical core. For the latter SCK•CEN joined the network as a new partner. Apart from the existing strong links with GANIL (France) and GSI (Germany) new links with research groups from CSNSM (Orsay, France) and the university of Köln (Germany) were established. Some of the topics that are addressed in the present phase are a continuation and extension of the research carried out under the previous IAP phases, others are new topics centered on exotic nuclei and using novel instrumentation and new theoretical approaches.

1.4 General objectives of the research project and of the partnership

The proposed BriX-network brings together the Belgian expertise on theoretical and experimental nuclear physics, nuclear astrophysics and accelerator driven systems, and executes, in a coherent and collaborative effort, a research program focused around radioactive ion beam research. Together with the EU partners, a carefully selected sample of atomic nuclei most of them with extreme proton to neutron ratios will be studied to bring key elements for a better understanding of the manifestation of the strong, weak and electromagnetic interaction in the nuclear medium.

Key experiments on the properties of exotic nuclei through decay, moment and reactivity measurements are proposed while the beta decay of specific isotopes will serve the weak interaction studies. Theoretical studies are directed towards few-body models, mean-field descriptions and shell models and their symmetries. The results will be used for nuclear-structure studies, weak interaction studies and nuclear astrophysics, as well as to investigate fundamental nuclear physics opportunities offered by accelerator driven systems, more specifically the MYRRHA project at SCK•CEN.

The network is based on a well established collaboration between the partners from the previous phase (K.U.Leuven, ULB, UGent, GANIL and GSI) and has been extended with the experimental neutron physics group from UGent and the MYRHHA SCK•CEN group specialized in accelerator driven systems. New EU partners are the Institute of Nuclear Physics of the University of Köln, UNI Köln (Köln, Germany) and the Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, CSNSM (Orsay, France). These new partners bring novel expertise and re-enforce existing expertise in the network: high-level instrumentation for gamma-ray detection, in-beam spectroscopy, lifetime measurements, neutron physics, high-intensity proton radiation target stations, symmetry based nuclear modeling, mean-field calculations to name a few. This together with an increased emphasis on exotic nuclei research and the embryonic study of some fundamental aspects of ADS introduced a focused program where theory and experiment are closely linked. Because of administrative reasons, ISOLDE-CERN could not be partner in the BriX network, but as will become clear, the ISOLDE facility plays an essential role in the network. Experimental campaigns at the radioactive beam facilities of Louvain-la-Neuve (Belgium), ISOLDE-CERN (Switzerland), GANIL (France) and GSI (Darmstadt) and at the SCK•CEN and GELINA (Belgium) neutron facilities will be executed. The partnership between theoretical, experimental and applied nuclear physics research groups should result in an added value that is not only reflected in a number of co-publications, but also in new joint initiatives for beam time and research programs, for the development and use of novel instrumentation as well as for increasing the quality of the post-graduate university education.

This proposed research program covers the following topics:

- Study of light exotic nuclei: structure, decay properties and reactivity: few-nucleon correlation effects, clusters structures, halo and skin structures

- Study of medium-heavy and heavy nuclei with a closed shell configurations for protons or neutrons: effective interactions in nuclei with extreme N/Z ratio, shape coexistence

- Study of nuclei along the N=Z line: pairing correlations, deformation driving phenomena, exotic decay modes, T=1 and T=0 interactions, weak interactions

- Set-up effective interactions that will allow unrestricted shell-model studies for the largest possible model spaces in order to explore better the extremes of the nuclear shell model and an effective interaction, in the form of an energy density functional, in conjunction with a beyond mean-field method.

- Study of the nuclear physics aspects of reactions of astrophysics interest

- Study of rare actinides: nuclear structure, neutron-capture, accelerator driven systems

The study of these topics, together with the experimental tools (instrumentation) and theoretical tools that need to be developed, resulted in a number of objectives:

Objective 1:
We want to increase the selectivity of the LISOL laser ion source and to optimize the experimental conditions at the Penning trap based WITCH (ISOLDE) and SHIPTRAP (GSI) projects.

Objective 2:
We want to model and analyze a selected set of nuclear reactions of astrophysics interest, including an experimental study of neutron-capture reactions.

Objective 3:
We want to investigate the properties of key states in light exotic nuclei, compare them with the theoretical models developed within the collaboration, and understand the possible influence on the reaction mechanism at energies around the Coulomb barrier.

Objective 4:
We want to study medium-heavy and heavy closed shell nuclei in order to obtain key information to test and improve the predictive power of nuclear models far from stability

Objective 5:
We want to study the nuclei along the N=Z line elucidating the neutron-proton pairing interaction, verifying isospin symmetry and studying the weak interaction in the atomic nucleus.

Objective 6:
We want to study neutron-capture reactions on rare isotopes of interest for astrophysical and nuclear waste transmutation processes.

Objective 7:
We want to investigate the feasibility of using the high power proton beam that will become available in the MYRRHA accelerator driven system for Belgian fundamental nuclear-physics research.

2. RESEARCH RESULTS (01/01/2007 – 30/04/2010)

A summary of the results is given per work package. The involvement of the different partners in the work is given in brackets for every sub item (most of the work is performed in an international collaboration, but for the present report we mention only the partners of the IAP BriX network). At the end of every work package (or at the end of a sub-item of it) a short conclusion and the main achievements are summarized. If a deviation from the original plan was encountered it is explicitly mentioned. More detailed information including the publications resulting from this work can be found in the annual reports 2007 – 2008 and in the 2009 – 2010 list of publications that is given at the end of this report. The research highlights are discussed under 4.1.

Work package 1: Preparation of radioactive ion beams

1.1 Optimization of the LISOL laser ion source and development of new laser ionization schemes (K.U.Leuven, GSI, GANIL)

The newly designed and constructed dual chamber gas cell has been fully characterized and used for in-source laser spectroscopy of neutron-deficient Cu isotopes (including the N=28 ^{57}Cu) and, in the near future, of neutron-deficient Ag isotopes (including the N=50 ^{97}Ag).

An extensive off- and on-line study program was undertaken to optimize the efficiency and selectivity of the laser ion source whereby proton-induced fission as well as heavy (and light) ion fusion evaporation reactions were used. Efficiencies up to 4% and a selectivity above 2200 were achieved by applying electrical fields inside the gas cell to collect the unwanted ions and to guide the wanted photo ions. The performance of the gas cell (gas flow and electrical fields) has been simulated and compared with experimental data. Furthermore the Laser Ion Source Trap (LIST) mode, coupled to a gas cell was demonstrated, but could not be fully exploited because of the limited repetition rate of our laser system. These results have been published.

The improved conditions allowed us to prepare and optimize the set-up for in-source laser spectroscopy experiments. This technique suffers from a reduced resolution, but has a superior sensitivity compared to collinear laser spectroscopy studies. We have demonstrated this by measuring the magnetic moment of ^{57}Cu, the one-proton neighbor of the doubly-magic ^{56}Ni nucleus, which has half-life of 199 ms and a production rate of only 6 atoms per second (see under WP 5). Recently, we performed production test for neutron deficient Ag isotopes and could prove that laser spectroscopy of the semi-magic nucleus ^{97}Ag will be possible. Experiments are planned for June 2010. A great leap forward in the use of the gas cell for laser spectroscopy purposes has been achieved with the discovery of our ability to create photo-ions with good laser spectroscopy resolution in many different conditions, either outside the gas catcher in the radio frequency ion guide or at low pressure in the gas catcher itself. By sending the laser beam through the exit hole of the gas cell and applying a positive voltage on the Sextupole Ion Guide (SPIG) rods to prevent ions from the gas cell to reach the SPIG, we were able to prove the feasibility of the so-called Laser Ion Source Trap (LIST) mode. The repetition rate of our laser system is however too small to be able to obtain a reasonable efficiency. In the course of this work, we discovered an important limitation on the achievable selectivity for the

laser ion sources using a radiofrequency (RF) structure (e.g. the SPIG) to guide the ions from the exit of the ion source to the accelerating zone of the mass separator. In these systems, an important part of the neutral radioactive atoms are captured on the electrodes of the RF structure. After radioactive decay, the decay products are released from the rods and captured in the pseudo potential of the RF structure which might give rise to an important isobaric contamination. Further research is underway to solve this problem.

To prepare a long-term future, a new project was initiated to couple a laser based gas cell to the focal plane of the S3 project (Super Separator Spectrometer coupled to the high-intensity heavy-ion accelerator of the SPIRAL-2 project at GANIL, France). This should allow the production and study (decay studies and in-source laser spectroscopy studies) in totally unexplored areas of the nuclear chart (e.g. ^{94}Ag and its isomers, ^{100}Sn and the Z>90 region). Technical design studies and first physics cases has been worked out and a specific test program to establish the performances of the LIST mode has been partially executed. Specific tests have been performed at the LISOL set-up. The plan is to move this set-up in 2012 to the GANIL site. This project has been endorsed by the GANIL scientific advisory committee. Finally, it should be mentioned that this technology is now being exported to RIKEN (Japan) where a gas cell is planned at the focal plane of the BigRIPS separator (the so-called PALIS project).

This R&D work has been performed in a large international collaboration and partially in the framework of the EURONS Integrated Infrastructure Initiative project.

1.2 Optimisation of the overall experimental conditions at SHIPTRAP related to studies along the N=Z line (K.U.Leuven, GSI)

Two major physics programs were discussed to be executed at the SHIPTRAP set-up at GSI. The first one the direct mass measurement of the newly identified isomer in ^{67}Co at the LISOL facility (see WP 4.2). This measurement, however, was executed at MSU. After evaluating the quality of the MSU results (private communication), it was decided not to repeat this measurement. The second project was to determine the position of the different isomers in ^{94}Ag and the mass of the neighboring nuclei. This is, amongst others, crucial to finalize the discussion on the proton and possible two-proton decay of the 21^+ isomer. In preparation of this project, one preferably should find ways to enhance/reduce the isomers prior to injecting them into the measuring trap. Resonant laser ionization is an ideal way to enhance/reduce certain isomers by making use of the specific hyperfine splitting of the isomeric states. The laser development work is still ongoing (see WP 1.1 and 5.1) and will be finished before an attempt to measure the masses of the ^{94}Ag isomers and neighboring nuclei can be undertaken.

1.3 Feasibility study to perform spectroscopy measurements with WICH and SHIPTRAP (K.U.Leuven, GSI)

For WITCH two possible set-ups are being considered. The first is the installation of a tape station on top of the WITCH apparatus. Simulations have shown that a narrow (few millimetre diameter) beam spot can be created on the tape when ions are expelled from the WITCH Penning ion trap and are accelerated to about 5 -10 keV. Simulations also learned that the large electrode of the retardation spectrometer can be used for this purpose.

The second set-up is a new and compact beta spectrometer consisting of a multi-wire drift chamber for electron tracking and a semiconductor detector for the energy determination. Such a combination allows one to reject events that were (back)scattered on the energy detector, and could have an efficiency that is about two orders of magnitude larger than that of the 'classical' magnetic beta spectrometers.
Installing this spectrometer behind the WITCH Penning ion traps will, in addition, provide a scattering free source. Tests with a small prototype drift chamber with cubic symmetry have yielded good results. As simulations showed that a hexagonal geometry would be more favorable (e.g. to reduce scattering on the wires) a new prototype was developed and successfully tested as well. Further, materials that can be used for the required window between the drift chamber and the energy detector were selected, while measurements to test the operation of a Si PIN diode in a He gas atmosphere, in electrical fields and in large magnetic fields, as will be present in the drift chamber were performed as well.

Deviation from the initial program:
In order to keep the necessary coherence in the research program and because important laser developments were not fully completed, the Belgian network partners were so far not involved in the optimization of SHIPTRAP at GSI (item 1.2 and 1.3) but intensified the other activities related to GSI, namely the beta-delayed fission characterization, the alpha decay studies at SHIP and finalizing the RISING activities. It is important to note however that the development of the SHIPTRAP set-up at GSI has resulted in a number of highlights (e.g. the mass measurement of $^{252-254}$No: M. Block et al., *Nature* 463, 785-788, 2010). In view of the new opportunities offered by the FAIR project and its consequences on the current GSI program a thematic BriX workshop will be organized in the Fall of 2010 to discuss and investigate possible new opportunities on the short (2011) and the long term for the collaboration between GSI and the Belgian BriX partners.

Main achievements and conclusion:
The performance of the gas cell based laser ion source has been vastly improved and allowed unprecedented nuclear-structure physics measurements. This development will be exported to the S3 project (SPIRAL-2, GANIL) aiming for an increase in production rates over two orders of magnitude and the acquired know-how will be used at other projects at GSI, Germany and RIKEN, Japan.
Extended simulations and test experiments have shown that the WITCH set-up can be used for sensitive spectroscopy measurements.

Work package 2: Study of reactions of astrophysics interest

2.1 Theoretical study of nuclear reactions of astrophysical interest: microscopic models, direct reactions and R-matrix analysis *(ULB)*

Scattering lengths
Low-energy cross sections can be parameterized by effective-range expansions. However, except for the scattering length in neutron elastic scattering, its coefficients cannot often be measured with accuracy. We have used the Resonating Group Method to derive the scattering

length and effective range for elastic scattering, and the S-factor expansion near zero energy for capture reactions. Scattering lengths and effective ranges consistent with existing data have been determined in this way for the α+n, ^{16}O+n, ^{14}C+n neutron scatterings, α+p, ^{16}O+p, ^{14}O+p proton scatterings, and $\alpha+\alpha$, $\alpha+^{3}$H, $\alpha+^{3}$He collisions between light ions. An S-factor expansion consistent with existing data has been determined in this way for the ^{16}O(n,γ), ^{16}O(p,γ), ^{14}C(n,γ), ^{3}H(α,γ), ^{3}He(α,γ) radiative captures. The results provide a simple parameterization of the radiative-capture cross sections at low energies.

Microscopic studies of the $^{12}C(\alpha,\gamma)^{16}O$ and $^{18}F(p,\alpha)^{15}O$ reactions

The ^{12}C(α,γ)^{16}O reaction plays a crucial role in nuclear astrophysics, but obtaining the cross section raises many difficulties, on the theoretical as well as on the experimental sides. We have investigated the E2 cross section in a microscopic cluster model involving all p-shell states of ^{12}C. This microscopic analysis has been complemented by a phenomenological R-matrix approach. We have shown that current data on capture and elastic scattering do not allow a precise determination of the rate, and we have suggested that a re-measurement of cascade transition to the 2+ state is desirable to constrain the S-factor.

The ^{18}F(p,α)^{15}O cross section has been measured by the CSNSM group at Louvain-la-Neuve at very low energies (down to 400 keV). This reaction plays a key role in novae physics, but the reaction rate remains very uncertain. The main reason is that the cross section is affected by several low-energy resonances whose properties are poorly known (or not known at all). The ULB contribution in this collaboration was to perform an R-matrix fit of the S-factor, by including the new data, as well as previous data.

Indirect methods

We have addressed the problem of charge symmetry of Asymptotic Normalization Constants (ANC) within a microscopic model. In many pairs of mirror systems, one of the nuclei is easier to investigate experimentally. In that case, the link between the ANCs is an important issue. This link has been established on the basis of simple assumptions, but needs to be tested by elaborated models. We have used a microscopic cluster model to investigate the charge symmetry of ANCs in α+nucleus systems. We have determined the ANC of some pairs of mirror nuclei ($\alpha+^{15}$N/^{15}O, $\alpha+^{7}$Be/^{7}Li, etc) and compared their ratios with the simple approximation. On the other hand, we have used this formalism to investigate the ^{26}Si(p,γ)^{27}P reaction from the experimental ANC of the ^{27}Mg mirror nucleus.

2.2 Theoretical and experimental study of neutron capture reactions of astrophysical interest (ULB, UGent)

Experimental study

The ^{26}Al(n,α)^{23}Na reaction cross section has been measured at the GELINA neutron spectrometer of the Institute for Reference Materials and Measurements (IRMM) in Geel up to about 100 keV, using the time-of-flight technique. A Frisch-gridded ionization chamber with ultra pure methane as detector gas was used for the detection of the α particles. Six resonances could be observed in this energy region, whereas before only one had been identified experimentally. From the obtained ^{26}Al(n,α)^{23}Na reaction cross section data, Maxwellian

averaged cross section values (MACS) for stellar temperatures up to 45 keV were calculated by numerical integration. Since neutron induced reactions are amongst the major destruction mechanisms of ^{26}Al in our Galaxy, these new MACS values contribute to a better understanding of the observed ^{26}Al abundance. The results have been published. Also the ^{41}Ca(n,α)^{38}Ar reaction cross section was measured at the GELINA neutron spectrometer using another Frisch-gridded ionization chamber, optimized for the study of this reaction. The measurements were performed at a 30 meter long flight path using the time-of-flight technique and they cover neutron energies from a few eV up to about 100 keV. The data are being analyzed and the results will be presented at NIC2010 in Heidelberg.

Parametrization of low-energy cross sections for non-resonant neutron capture

The non-resonant component of radiative neutron capture reactions can be accurately parametrized at low energies by a polynomial of second degree of the energy. The potential model is first used to reproduce experimental data below 1 MeV with the help of spectroscopic factors. The fits are found sensitive to the scattering length of the initial s or p waves. The coefficients of a Taylor expansion are then calculated by resolution of the Schrödinger equation and its energy derivatives at energy zero. The resulting polynomial fits the data and allows one to interpolate them. Such theory-guided parametrizations are derived for neutron capture by ^{7}Li, ^{12}C, ^{14}C, ^{16}O, and ^{18}O. When the capture proceeds from the s wave to a weakly-bound state, a Padé-like parametrization better approximates the potential-model results.

Main achievements and conclusion:

The objective was to determine the ^{26}Al and ^{41}Ca(n,α) cross sections as a function of the neutron energy and to transform them into MACS as a function of stellar temperature. This goal has been reached for ^{26}Al and it will be achieved for ^{41}Ca before the end of the project. Furthermore, various reactions of astrophysical interest have been investigated. A new method to derive the zero-energy expansion of the S-factor has been developed and the ^{12}C(α,γ)^{16}O cross section was re-analysed resulting in a new proposal for an indirect method to constrain the E2 contribution.

Workpackage 3:Light exotic nuclei

3.1 Experimental investigation of the structure of light nuclei (K.U.Leuven – ULB – GANIL)

Beta decay of ^{8}B

The solar-neutrino detectors Super-Kamiokande, SNO and ICARUS are primarily sensitive to electron neutrino's, νe, from the β-decay of ^{8}B. Neutrino oscillations are invoked to explain the presence of ν,μ,τ components in the measured flux. Such a solution implies the distortion of the measured spectrum of solar neutrinos with respect to the unperturbed one. Thanks to the increasing accuracy of the solar neutrino measurements, the differences between the two spectra can be used to set constraints on the parameters of neutrino oscillations. With the aim of improving on the existing data, we performed a measurement at the TRIμP (Trapped Radioactive Isotopes: μicro-laboratories for Fundamental Physics) facility at KVI (Kernfysisch

Versneller Instituut) , Groningen (The Netherlands) using a calorimetric technique developed by our collaboration. This technique should allow to obtain spectra with a low-energy threshold down to 200 keV. The data is currently being analyzed. Along the same lines a study of excited states in ^{12}C (e.g. the Hoyle state) was performed using the same set-up and complemented with measurements performed at the accelerator centre of the University of Jyväskylä (Finland). The results have been published.

Beta decay of ^{11}Li and ^{11}Be and transfer reactions on ^{11}Be

The beta-delayed deuteron and triton decay of ^{11}Li has been studied and published while the analysis of the ^{11}Be beta decay populated in the beta decay of ^{11}Li (data obtained at TRIUMF using our calorimetric detection system) is finished and evidenced the existence of a strongly populated resonance above the beta-decay window. A short experiment using our detector at the REX-ISOLDE facility using a ^{11}Be beam allowed us to establish a new value for the feeding of bound states in the decay of ^{11}Li, a value that is sensitive to the involved single-particle components. Finally, a first attempt to study the low-energy transfer reactions on ^{11}Be was undertaken. This experiment aiming at studying the character of the excited resonances in $^{10,12}Be$ will be repeated in 2010.

Ground state moments of ^{11}Li and ^{11}Be

The magnetic dipole and electric quadrupole moment of the one-neutron-halo nucleus ^{11}Li have been measured to an order of magnitude better precision than before. These values, along with the recently measured changes in mean square charge radii, provide a stringent test for various nuclear models. It seems difficult to reproduce in a consistent manner the increase in the quadrupole moment and the increase of the charge radius of the halo-nucleus with respect to those of its ^{9}Li core. The trend in the quadrupole moments is very well reproduced by *ab-initio* shell model calculations, but the absolute values are underestimated. The mean square charge radius of the one-neutron halo nucleus ^{11}Be has been measured at ISOLDE (GSI – Leuven). A good agreement has been observed with *ab-initio* shell model calculations.

Single particle state in ^{19}Na

At the Louvain-la-Neuve radioactive ion beam facility the $H(^{18}Ne,p)^{18}Ne$(g.s.) and $H(^{18}Ne,p')^{18}Ne^{*}(2^{+}$, 1.887 MeV) cross sections have been measured using a ^{18}Ne beam at energies corresponding to the excitation energy range between 2 and 3 MeV. The elastic and inelastic data have been analyzed simultaneously by using the R-matrix method and two new states in ^{19}Na have been observed. The data have been published.

Main achievements and conclusion:

The calorimetric detection systems developed by the BriX collaboration has been used successfully to study beta-delayed charged particle emission at different radioactive beam facilities (TRIUMF, KVI, ISOLDE) and showed to produce high-quality data that confirm the ingredients used in state-of-the-art theories.

3.2 Reaction studies around the Coulomb barrier (K.U.Leuven - GANIL)

Experimental study

At the Cyclotron Research Centre in Louvain-la-Neuve the elastic cross section of ^{6}He on a ^{238}U target at energies around the Coulomb barrier was performed in order to compare the behavior of ^{6}He with that of ^{4}He; to extract reliable Optical Model parameters, which are an important ingredient in models for the calculation of the cross sections; and to derive limits on the total cross section. At the same time, the fusion and transfer cross sections were re-measured. The position-sensitive detectors were used here for the first time and their performance was good and reliable. The analysis is close to be finished. Parallel to this program the astrophysically important ^{14}O(α,p)^{17}F was studied in time reverse kinematics at REX-ISOLDE, CERN. In particular, the highly efficient MINIBALL detection system was used to measure the previously undetermined inelastic proton branch of the 1^{-} state at 6.15 MeV in ^{18}Ne. This state dominates the reaction rate under X-ray burster conditions.

The CDCC method

The CDCC (Continuum Discretized Coupled Channels) method has many applications in nuclear physics, in particular for reactions near the Coulomb barrier. It provides a quantum treatment of various processes (elastic and inelastic scattering, breakup, etc), since the projectile is described by a cluster structure. The method is well suited to exotic nuclei, where breakup channels play an important role. These breakup channels are approximated by square-integrable wave functions, aimed at simulate continuum states of the projectile. Our specific contribution is to adapt the R-matrix theory to CDCC, and to use Lagrange functions to describe the projectile-target motion. This provides an accurate and efficient framework for the CDCC method. We have started with the d+^{58}Ni system at E_{lab}=80 MeV, which is considered as a standard benchmark in the literature.

3.3 Development and exploitation of cluster models and experimental investigation of light exotic nuclei using beta decay and reaction studies (ULB – K.U.Leuven)

Microscopic cluster description of light nuclei

Some three-body systems (^{5}H, ^{5}He, ^{18}Ne) have been investigated in a microscopic cluster model. We have used the three-cluster Generator Coordinate Method associated with the hyperspherical formalism. The properties (energies and widths) of unbound states have by using the "Analytic Continuation in the Coupling Constant" (ACCC) method, based on Padé approximants.

We have studied the ^{12}Be nucleus in a microscopic cluster model involving the ^{6}He+^{6}He and α+^{8}He configurations, as well as some of their excited states. We have analyzed the band structure of ^{12}Be, by focussing on “molecular” states. In a second step we have started an analysis based on the “No Core Shell Model” (NCSM). Both approaches applied to a common problem provide useful information about the advantages and limitations of these models.

Renormalized RGM

Microscopic cluster models are based on fundamental principles of quantum physics, such as the Pauli principle, but require in general rather heavy numerical calculations. The Resonating Group Method (RGM) for example assumes that a nucleus presents a substructure, composed of clusters. In collaboration with Y. Suzuki (Niigata, Japan) and Y. Fujiwara (Kyoto, Japan), we

have reformulated the RGM equation in order to derive an equivalent nucleus-nucleus potential. We have determined α+n and $\alpha+\alpha$ potentials and used them in 3-body systems: ^{6}He=α+n+n, ^{9}Be=$\alpha+\alpha$+n and ^{12}C=$\alpha+\alpha+\alpha$.

Use of realistic nucleon-nucleon interactions in reaction cluster models

We have started a new study aiming at using realistic nucleon-nucleon interactions, i.e. interactions that fit the nucleon-nucleon scattering data with high precision, in microscopic cluster models.

In addition, we are collaborating with the Niigata group on the d+d system with realistic nucleon-nucleon interactions. We have started with elastic scattering, and plan to investigate the d(d,γ)^{4}He capture reaction in a near future. The current results suggest that the ^{3}H+p and ^{3}He+n configurations should be included. This work is in progress.

Analytical properties of the two-body elastic scattering matrix

We have established the condition under which a two-body loosely bound state has an influence on low energy elastic scattering properties. For that, the interaction potential should have a short enough range. Several examples illustrating this behaviour have been studied and, in cases where such influence exists, two general relations between scattering and bound-state properties have been established. The first relation, based on the position of the scattering matrix pole in the complex wave number plane, relates the effective-range expansion with the binding energy. The second relation, based on the residue of this pole, relates the effective-range expansion to the asymptotic normalization constant of the bound state. We have tested the precision and utility of these relations on simple nuclear systems (^{16}O+p, ^{16}O+n, ^{12}C+α).

Continuum states with the Green's function formalism

A new method to obtain both the wave function and S matrix for coupled-channels scattering problems has been derived in collaboration with Y. Suzuki (Niigata, Japan) and A. Kievski (Pisa, Italy). The method is characterized by the introduction of a real confining potential acting in the external region, which enables one to solve the problem using only bound-state solutions. The asymptotic behaviour of the continuum state is guaranteed with a single-channel Green function. The accuracy and simplicity of the method are demonstrated on two examples: an exactly solvable two-channel potential and nucleon-nucleon scattering.

Three-body continuum states

We have investigated three-α continuum states in the hyperspherical formalism for $J^{\pi}=0^{+}$ and $J^{\pi}=2^{+}$. Two different types of $\alpha+\alpha$ interactions were used: the shallow Ali-Bodmer potential and the deep potential of Buck et al. We have determined the three-alpha phase shifts up to E=6 MeV, in parallel with an analysis of resonances in the framework of the Complex Scaling method. We have shown that shallow potentials provide additional narrow resonances, in contrast with experimental data. Deep potentials, however, only give rise to broad resonances, and are more consistent with the data.

In parallel, we have developed a microscopic approach, based on a nucleon-nucleon interaction. We use the Generator Coordinate Method, associated with the hyperspherical formalism for 3-body states. In the present case, a fully numerical treatment is very heavy, and a semi-analytical

approach, involving symbolic computing, has been developed. We have started with α+n+n three-body states, and computed various eigenphases. We have confirmed the existence of a low-lying 1- resonance, predicted by non-microscopic approaches. Then the calculation has been extended to the mirror system, α+p+p, where the Coulomb force must be included. The spin-orbit force has also been taken into account. We are now working on heavier systems, such as $\alpha+\alpha$+n and $\alpha+\alpha$+p.

Exactly-solvable coupled-channel models from supersymmetric quantum mechanics

Several studies have been performed in the framework of supersymmetry transformations applied to coupled systems of radial Schrödinger equations, in collaboration with B. Samsonov and A. Pupasov (Tomsk State University, Russia). These works aim at constructing exactly-solvable models, with well-controlled properties, both for bound and scattering states. As such they can be considered as particular solutions of the quantum scattering inverse problem, for coupled channels characterized both by equal and different thresholds.

In the different-threshold case, we have reformulated in terms of supersymmetric transformations a potential known in the literature as the Cox potential. Our construction method allows both its generalization and a much simpler study of its properties. As first physical applications, we have used this potential to describe atom-atom interactions, which have simplifying features with respect to nucleus-nucleus interactions (no Coulomb potential, as atoms are neutral; physical relevance of coupled s waves). In particular, we have described analytically the interaction between a Feshbach resonance and a bound- or virtual-state close to threshold.

In the equal-threshold case, we have considered several types of transformations introducing a coupling between initially decoupled channels. Pairs of supersymmetric transformations, with purely imaginary and mutually adjoint factorization energies, have been found to be particularly useful, as they modify the coupling parameter appearing in the scattering matrix, while leaving eigenphase shifts unchanged. This opens the way to a new solution of the coupled-channel inverse scattering problem. We have constructed a schematic two-channel example, coupling s and d waves, and are currently extending it to the construction of realistic nucleon-nucleon interactions. In the future, we hope to also apply these methods to low-energy nuclear collisions and reactions.

3.4 Development and exploitation of break-up models for intermediate and relativistic energy reactions with light exotic nuclei (ULB – GSI)

Breakup reactions

Breakup reactions are one of the main tools for the study of exotic nuclei. In particular, Coulomb breakup is expected to provide information on spectroscopic properties of halo nuclei and on astrophysical S factors for radiative-capture reactions. The simplest studies are based on perturbation theory and especially on its first order. However the validity of the first-order approximation may be limited for extended systems such as halo nuclei and its conditions are not always satisfied in existing experiments. In recent years, we have developed more elaborate reaction models: resolution of the semi-classical time-dependent Schrödinger equation, eikonal and dynamical eikonal (DEA) approximations. These methods were first applied to the ^{11}Be and

^8B breakup. The latter process is expected to be related to the $^7Be(p,\gamma)^8B$ reaction at stellar energies

We have also applied the DEA to the elastic breakup of ^{19}C (=^{18}C+n) and ^{31}Ne (=^{30}Ne +n) on ^{208}Pb. A $d_{5/2}$ resonance in ^{19}C is expected to influence the breakup cross section but its location is unknown. The ^{31}Ne nucleus is close to the neutron drip line and may belong to an "island of inversion" where the ground state occupies an intruder $p_{3/2}$ orbital in place of the $f_{7/2}$ orbital suggested by the naive shell model. The comparison of the calculation with recent RIKEN data clearly indicates that the ground state should be the intruder state.

The traditional eikonal approximation suffers from a divergence problem at large impact parameters associated with the treatment of the Coulomb interaction. In collaboration with Y. Suzuki (Niigata University, Japan), we have developed the Coulomb-corrected eikonal approximation (CCE) which reproduces with a satisfactory accuracy most of the observables obtained with the more elaborate DEA. The CCE has been extended to the investigation of the elastic breakup of three-body projectiles at intermediate and high energies. The initial bound states and the final scattering states are calculated in hyperspherical coordinates on a Lagrange mesh following a procedure developed by our group in recent years. The model has been applied to the breakup of ^6He on ^{208}Pb at energies typical of RIKEN and GSI experiments. The ^6He halo nucleus is described within a three-body α + n + n model involving effective α + n and n + n interactions.

Practical methods to compute dipole strengths for a three-body system making use of a discretized continuum and thus avoiding the complicated construction of three-body scattering states have been studied in collaboration with Y. Suzuki. New techniques involving a Green function have been developed. They should allow simpler determinations of the E1 strengths of two-neutron halo nuclei.

High-energy elastic scattering with microscopic wave functions

We have applied the eikonal method to α+nucleus elastic scattering at high energies, by considering the internal structure of the α particle. This represents a first step of a more ambitious project, where the projectile would be described by a microscopic model with a two (or three) cluster structure. This would allow describing breakup reactions. One of the main advantages is that the present approach does not need any nucleus-nucleus optical potential. These potentials are in general poorly known, in particular for exotic nuclei where very few data (or no data) exist. We have applied the microscopic technique to $\alpha+^{208}Pb$ and $\alpha+^{58}Ni$ at E_{lab} = 288 MeV.

Main achievements and conclusion

Several aspects of nuclear reactions have been investigated, either to develop theoretical models, or to provide a theoretical support to experiment. Elastic and breakup cross sections have been determined in different approaches. We have analysed various aspects of the nucleon-nucleon and nucleus-nucleus interaction. Models for three-body continuum states have been developed, and used to compute 3-body breakup cross sections.

Workpackage 4: Studies of medium-heavy and heavy closed shell nuclei

*4.1 Study of the changing shell structure in neutron rich nuclei near N=20 and N=28 (*K.U.Leuven – ULB – UGent – GANIL – CSNSM – U.Köln)

The 'island of inversion' around ^{32}Mg (N=20) is a region of nuclei with a ground state dominated by particle-hole excitations of neutrons from the *sd*-shell into the *pf*-shell (called 'intruder' ground state configuration). Measurements of moments and spins have been performed to study the transition from the region of normal sd-shell isotopes towards the 'island of inversion'. Ground state spins and magnetic moments of $^{21-33}$Mg isotopes (Z=12, N=9-21) were measured at ISOLDE-CERN, while the g-factors and quadrupole moments of $^{31-34}$Al isotopes (Z=13, N=18-21) were being investigated at the LISE fragment separator at GANIL. The data reveal a gradual transition from the normal region into the island of inversion, both along N and along Z. The ^{33,34}Al isotopes act as 'transitional nuclei', having a mixed normal/intruder g.s. wave function. In the Mg chain, the spins and moments of ^{31}Mg and ^{33}Mg isotopes reveal a pure 2p-2h intruder g.s. configuration. The data allowed testing the validity of recent large-scale shell-model effective interactions, and modifications to the effective interactions were proposed based on the obtained results.

Towards N=28, the $^{41-44}$Cl ground states (Z=17) were investigated at GANIL with β-NMR (Leuven-GANIL). An inversion between $\pi s_{1/2}$ and $\pi d_{3/2}$ configurations is suggested to occur around ^{41}Cl. The measured g-factor of ^{44}Cl is in agreement with a suggested 2^+ ground state and it reveals the influence of neutrons excited across N=28, as well as the inversion of the proton orbits. No significant resonance effect (within 0.5%) was observed for ^{41,42,43}Cl. The non-observation of resonances for ^{41}Cl and ^{43}Cl is a strong indication for their ground state to have a spin $1/2^+$, dominated by the proton $\pi s_{1/2}$ hole configuration. Indeed, for isotopes with the last nucleon in a spherical $s_{1/2}$ orbital, the polarization is expected to be very small.

A proposal to study the ground state spins and magnetic moments (to get information on the ground state structure) of the neutron-rich K-isotopes has been accepted at ISOLDE (Leuven – GSI). The goal is to investigate the evolution of the proton single particle levels when filling the $\nu p_{3/2}$ orbital, beyond N=28. Theoretical models predict that the $\pi s_{1/2}$ and $\pi d_{3/2}$ levels will repel again (after they became near-degenerate towards N=28), but little or no experimental data are available to confirm/reject this. A first experiment is scheduled for November 2010. During the remaining period of the IAP, the quadrupole moments of ^{33,34}Al will be measured (beam time scheduled July 2010 at GANIL) to confirm the intruder mixing in their wave function (deduced from g-factors), and establish the amount of mixing. The ^{41}Cl β-NMR resonance will be re-measured, looking for a resonance effect of <0.5% (beam time scheduled July 2010 at GANIL) to establish its ground state spin (1/2 or 3/2) and the hyperfine structures of ^{48,49,50,51}K will be measured to determine their g.s. spin and magnetic moment (scheduled November 2010 at ISOLDE).

Complementary to the above mentioned experiments, transfer reactions and Coulomb excitation experiments were performed using the post-accelerated Mg and Na beams from REX-ISOLDE and the MINIBALL detector array. The ^{30}Mg(d,p) reaction was studied and revealed the spin/parity and the single particle nature of the second excited state in ^{31}Mg. Using the ^{30}Mg(t,p) reaction allowed us to identify the first excited 0^+ state in ^{32}Mg. The energy of this state, together

with its pairing properties (to be deduced from the relative cross section of the excited state versus the ground state), will form stringent test to shell-model and mean field theories applied in this region of the chart of nuclei. The Coulomb excitation measurements of the neutron-rich Na isotopes will shed light on the role of the odd proton coupled to the ^{32}Mg core. The data are under analysis. In 2010-2011 campaigns are planned to extend the one-neutron transfer reactions to the Na isotopes and to complete the Na Coulomb excitation experiment will be completed.

Within the collaboration we have also concentrated on the E0 decay of the first excited 0^+_2 state and studied the ρ^2 value connecting to the ground state in ^{30}Mg. The observed small value indicates very small mixing, pointing towards coexisting configurations with different deformation, and has been interpreted within a two-state mixing model also. These results have been published.

All this new information is put in a larger picture of a review paper (Review of Modern Physics) were it will be pointed out that the competition between the monopole energy cost to create neutron 2p-2h excitations, on one hand, and the correlation energy gain, on the other hand, forms a unifying theme to describe low-lying intruder configurations and ‘islands of inversion’. This work is in progress.

Main achievements and conclusion:

For the first time, a β-NQR measurement was performed at GANIL to measure the quadrupole moments of exotic ground states (^{31,33}Al), using a dedicated set-up that has been developed within the BriX collaboration. The preliminary value for the ^{33}Al quadrupole moment illustrates that this N=20 isotone of ^{32}Mg has a mixed normal/intruder ground-state wave function. At ISOLDE, the combination of laser- and β–NMR spectroscopy on Mg isotopes allowed measuring the ^{31,33}Mg spins and signs of magnetic moments while the one- and two-neutron transfer reaction studies on ^{30}Mg allowed identifying and characterizing excited (intruder) states in ^{31,32}Mg. These firm assignments form stringent tests for shell-model and mean-field calculations in the N=20 region.

*4.2 The influence of exotic neutron-to-proton ratios on the shell structure and the onset of collectivity in the neutron-rich Z=28 region.(*K.U.Leuven – ULB - UGent – CSNSM – Köln – GANIL*)*

Laser spectroscopy and ground-state properties

In-source and collinear laser spectroscopy measurements on Cu (Z=29) and Ga (Z=31) isotopes were performed at ISOLDE-CERN using the ISCOOL cooler/buncher. The latter was developed in a large international collaboration including the BriX network. The improved sensitivity for collinear laser spectroscopy measurements reached nearly three orders of magnitude and allowed to extend the measurements towards ^{75}Cu (N=46) and ^{81}Ga (N=50). The inversion of the $\pi p_{3/2}$ and $\pi f_{5/2}$ single particle levels was observed as a change of the g.s. spin from $3/2^-$ to $5/2^-$ for ^{75}Cu and ^{81}Ga, their magnetic moments being close to the Schmidt moment for $\pi f_{5/2}$. The quadrupole moments of the odd-Ga isotopes suggest that already from N=42 onwards the $\pi f_{5/2}$

level is playing a dominant role in the g.s. wave function. This was also seen through the measured ground state spin of ^{72,74}Cu (N=43,45) for which a negative parity was found based on the measured magnetic moment. This negative parity is a signature for a major $[\pi f_{5/2}\nu g_{9/2}]_{2-}$ component in their ground state wave function. The A=61 up to A=75 Cu quadrupole and magnetic moments revealed the magic character of the N=40 semi-magic nucleon number, due to the parity-change between the *pf* and *g* orbits. An significant increase in the core polarization (similar as observed e.g. around ^{208}Pb) is observed when adding/removing neutrons with respect to N=40.

At GANIL, the quadrupole moment of an isomeric state produced by fragmentation was measured for the first time using the ion-gamma correlation method. The measured value for ^{61m}Fe, I=9/2, suggests an onset of deformation. The preparation and analysis of this experiment was done using a formal description of the perturbation pattern, developed within the BriX collaboration.

Coulomb excitation

Coulomb excitation measurements have been performed on the neutron-rich Ni, Zn and Cu isotopes. Results have been obtained on ^{68}Ni, up to ^{80}Zn (with a closed N=50 shell), up to ^{73}Cu and using isomeric beams from ^{68,70}Cu produced with selective laser ionization. Apart from the new data set on ^{70m}Cu, all data have been published. The ^{68}Ni result was in agreement with the result from intermediate Coulomb excitation performed at GANIL and confirm the low B(E2) value while the Zn isotopic chain indicate that in order to reproduce the data with large-scale shell-model calculations the polarization of the Z=28 is needed while it is not needed for the N=50 neutron shell. The Coulex data on the cupper isotopes show the existence of an unexpected low-lying excited state previously not observed in beta decay studies, exhibiting a degree of collectivity. This state can at present not be reproduced by theoretical models and evidences shape coexistence in the Cu isotopes. Furthermore the study proved that the $5/2^-$ state previously observed in beta decay studies and whose energy has a peculiar behaviour probably due to the filling of the neutron $g_{9/2}$ shell, has indeed a single particle structure. These data nicely complement the findings from the laser spectroscopy experiments mentioned above. Finally, the Coulex results on ^{73}Ga, combined with the laser spectroscopy measurements mentioned above, allowed us to establish a peculiar ground-state $1/2^-$ - $3/2^-$ doublet (probably) separated by less then 1 keV; this almost degeneracy of shape coexistent states is a challenge for theory.

In order to understand the structure of the nuclei in the $f_{7/2}$ proton shell, coulomb excitation experiments were prepared in the neutron-rich Fe isotopes (Z=26). Previous data from beta decay and deep-inelastic reactions indicate a swift onset of collectivity in these nuclei when moving away from Z=28 and towards N=40 and beyond. Due to their physico chemical properties, iron beams are not available at ISOLDE and a new production scheme had to be developed. This scheme consists of the production of intense beams of manganese, beta decay of the manganese to iron, capturing the recoiling iron ions in the Penning trap or the EBIS and post-accelerate to 3 MeV/u. First successful tests have been performed and beams of ^{61}Fe have been produced. The Coulomb excitation of ^{61}Mn and ^{61,62}Fe was studied. The analysis is in progress and part of the data has been published.

Decay studies

Two experimental campaigns were devoted to unravelling the structure of neutron-rich nuclei below the Z=28 proton closed shell. Making use of element-selective resonant laser ionization in a buffer gas cell combined with mass separation at the Leuven Isotope Separator On Line (LISOL) facility (Louvain-La-Neuve, Belgium), purified beams of short-lived neutron-rich $^{65\text{-}67}Fe$ isotopes were produced. The isotopes were created in a proton-induced fission reaction on ^{238}U and yields after mass separation were typically one ion per second. Their decay to $^{65\text{-}67}Co$ was studied using a newly developed detection station, which is digitally read out by XIA-DGF4C modules and which consists out of segmented germanium detectors of the MINIBALL type. The same experimental set-up was used at ISOLDE in 2009 for a decay study of a whole series of neutron-rich Mn isotopes (up to A=68) resulting in complementary information.

Thanks to the availability of weak, yet pure beams in low-background conditions, correlations between single γ and γ-coincident γ events were unambiguously established in the ^{67}Fe β decay. They fully characterized an isomeric state in ^{67}Co (Z=27, N=40) residing at an unexpected low excitation energy of 492 keV ($T_{1/2}$=0.50(3) s), which is interpreted as a 1-particle-2-hole (1p-2h) proton intruder state. The existence of this isomer has been confirmed in a recent mass measurement at MSU (U.S.A.). In ^{66}Co, a proton intruder state is observed at merely 176 keV above the ground state. The interactions used in state-of-the-art model calculations will have to be adapted to these findings. These results have been published. The observation of the low-lying isomeric state in ^{67}Co combined with the results from the Coulex measurements allowed us to compare the importance of the N=40 sub shell closure at ^{68}Ni with the Z=40 sub shell closure at ^{90}Zr. This comparison indicate a much higher degree of core polarization in case of Z=28 compared to N=50. From the low intruder excitation energy in ^{67}Co (492 keV) and the onset of collectivity in between N=40 and N=50 in the nickel and copper isotopes, one can expect that the intruder state becomes the ground state in the cobalt and iron isotopes beyond N=40, i.e., a new so-called “Island of inversion”. Furthermore, the $^{65\text{-}67}Co$ level schemes offer a well-suited testing ground for adjusting the effective interactions in this region. As such, it may become possible to describe quantitatively nuclei in the region around Z=28 and N=40 and to make predictions towards ^{78}Ni and the possibility of the suggested “'Island of inversion”' in the heavier cobalt and iron isotopes. The results from the LISOL experiment have been partially published, the data from ISOLDE are under analysis.

Transfer reactions

In 2009 a successful one-neutron transfer study on ^{66}Ni was performed using the newly built transfer reaction set-up at ISOLDE. In order to measure the population of a 13 microsecond isomer in ^{67}Ni a slow-correlation p-γ-delayed γ was developed by the BriX collaboration and used. Ample data were obtained and states up to 5 MeV in ^{67}Ni were observed. The experiment will shed light on the single-neutron hole character of the states and the data are under analysis The plans for 2010 and 2011 are to extend the set-up even more by adding a circular particle detector in the forward direction which will allow us to create a near 4π particle detection coverage and to perform the approved $^{78}Zn(d,p)^{79}Zn$ reactions which aim at structure studies in the region around ^{78}Ni. Also a proposal to study the $^{66}Ni(t,p)$ reaction (studying pairing around N=40) and $^{68}N(d,p)$ at low energy to complement the recent results obtained at higher beam energy at GANIL is under preparation.

Theory

These experiments have been complemented with theoretical efforts within the BriX collaboration, e.g. the question on how collective effects may result from large-scale shell model calculations has been addressed in the Cu and Zn region. Also the application of mean-field approaches was investigated, but was so far not successful. A systematic study of semi magic nuclei has demonstrated that this deficiency of mean-field methods is related to missing terms in the central part of the nuclear energy density functional. Further studies in this direction are still required. As a new topic within the context of the present work package, the study of collective motion, in particular isovector modes near closed shells, within the context of the nuclear shell model was initiated in the Sn region and the N=80 region. These studies identified excitations with a mixed-symmetry character in both the Cd and N=80 nuclei. A review on mixed-symmetric states has been written and is in print at Reviews of Modern Physics.

Main achievements and conclusion:

The combination of the direct spin measurements of neutron-rich Cu and Ga isotopes, the information on transition matrix elements in these nuclei, the observation of isomers below Z=28, the promising results from the one-neutron transfer reaction in this mass region and the large-scale shell model calculations, obtained from the work performed within the BriX network, form cornerstones for studying the monopole migration of the proton single particle orbits, the strength of the Z=28 and N=50 shell gaps as well as the fast onset of collectivity above and below Z=28.

4.3 Intruder states in the Pb region and the microscopic origin of collectivity (K.U.Leuven – ULB – UGent – GANIL – Köln – CSNSM - GSI)

Magnetic moment and mean square charge radii

For the first time it was possible to measure the quadrupole moment of a magnetic rotational band head in the Pb region. The ^{193m}Pb moment of the 9 ns isomeric band head was measured at Legnaro using the TDPAD method, and its spin was assigned based on the measured DCO ratios. The large quadrupole moment, similar to that of the 11^- intruder states in ^{192,194}Pb measured earlier, illustrates that the deformation in the magnetic rotational band is similar to that of the proton intruder component in its wave function. The deformation in the magnetic rotational band was deduced through comparison with the Tilted Axis Crancking model. Quadrupole moments of odd-neutron configurations have been measured as well, being significantly smaller.

To further explore the effect of shape coexistence in the vicinity of the magic shell closure at Z=82 (lead) but towards the neutron mid-shell (N=104), in-source laser spectroscopy experiments have been performed on the neutron-deficient polonium isotopes $^{191\text{-}216}$Po. Two experimental campaigns (2007 and 2009) allowed us to span the region from the very neutron-deficient to the very neutron-rich isotopes. The deduced mean-square charge radii show a strong deviation from the spherical liquid drop prediction for A<198 (N<114). This deviation occurs at a much larger neutron number compared to the Hg (N<106) and Pt (N<110) isotopes and is much more pronounced. Also on the neutron-rich side (beyond N=126) a clear kink in the

mean-square charge radii curve is observed similar to the Pb, Rn and Ra results. The former phenomena clearly indicate a swift onset of collectivity in the neutron-deficient polonium isotopes and can be interpreted as due to multi-particle multi-hole configurations present in the ground state. Essential for the extraction of these data were extended atomic physics calculations of the polonium atomic levels involved. Beyond mean-field calculations as well as symmetry based calculations have been performed to reproduce these findings in the polonium isotopes as well as within the lead data. The atomic physics and nuclear physics calculations were performed within our collaboration.

This program will be continued in 2010 and 2011 by investigating an ionisation scheme for the element astatine. As there are no stable isotopes available, this search has to be performed on-line. Once such a scheme is established a whole spectrum of new experimental possibilities becomes available including in-source laser spectroscopy.

Beta-delayed fission

In June 2008, a successful experiment was performed at the ISOLDE, in which the beta-delayed fission (BDF) of ^{180}Tl was searched for and studied in detail. The BDF is a very rare nuclear decay (so far only 10 cases are known in the uranium region), in which a parent (Z,A) nucleus first undergoes electron capture decay, populating excited states in the daughter (Z-1,A) nucleus, which then may fission with a certain probability. Such EC-delayed fission is of special interest because it allows to study the fission properties (e.g. decay probability, fission barrier height, mass/charge distribution, total kinetic energy, gamma and neutron multiplicities) of very exotic daughter nuclei, possessing a very low (in practice, un-measurable) spontaneous fission branch. During the run, approximately 107 decays of ^{180}Tl were observed, including more than 1300 singles BDF decays. A completely unexpected result of the experiment was the observation of asymmetric energy (thus, asymmetric mass distribution) of the fission fragments from ^{180}Hg, being the daughter of ^{180}Tl after beta decay. Apart from this, a new and precise BDF branching ratio was deduced for ^{180}Tl, which is by ~100 times larger than the previously reported value. Theoretical groups from Los Alamos (USA) and JAEA(Japan), working in the field of fission, have been involved in the interpretation of this phenomena which is currently understood as due to subtle effects in the saddle point. The data are submitted for publication. The data from the GSI experiment on the neutron-deficient At isotopes where a strong BDF branch was discovered, are being written up for publication and new campaigns are planned. Also a study of the fission process in this region using heavy ion fusion evaporation reactions has been performed at JAEA (Japan) and the analysis is in progress.

A new campaign to study beta-delayed fission of other Tl isotopes will take place in 2010 in order to explore the surprising asymmetric fission mode and to test the theoretical predictions.

Coulomb excitation of the neutron-deficient $^{188-182}$Hg and ^{200}Po isotopes

Since a clear shape dissimilarity in the ground state of light odd-mass mercury isotopes was observed by means of isotope shift measurements, shape coexistence in this mass region has been an intensively studied phenomenon by means of in-beam and decay spectroscopy. For light even-mass mercury isotopes, it has been advocated that a prolate band at low excitation energy is coexisting with an oblate ground state band. We performed Coulomb excitation at safe energies, a perfect technique to investigate the magnitude of transitions between low-lying

states, revealing information on the mixing of the different bands. Data were collected on $^{182,184,186,188}Hg$ and transitional quadrupole matrix elements as well as the sign of the diagonal matrix element of the first excited 2^+ state, containing the information about the nuclear quadrupole deformation, could be determined. In order to constraint the Coulomb excitation analysis, complementary life time measurements of the excited states in $^{184,186,188}Hg$ were performed using Gammasphere at Argonne National Laboratory (U.S.A.). Once these results are available a complete picture will evolve on the low-energy structure of these Hg isotopes and stringent test of beyond-mean field calculations will be performed. In the course of the BDF experiments (see above) new beta decay data ($^{180,182}Tl$ – $^{180,182}Hg$) were acquired. The beta decay data will help unravelling the Coulex experiments of the Hg isotopes. Also the Coulomb excitation of 200Po was performed with success. This is technically important as a large contamination of the radioactive ion beam was expected (mainly from Tl). However, carefully tuning the target-ion source system and the timing cycle allowed us to obtain high quality data. This experiment paves the way for a complete campaign of $^{196-202}Po$ that is planned for 2011 at ISOLDE.

Alpha decay studies

In the course of the BDF experiments at GSI (see above) new alpha decay data were acquired as well. These new data together with the large effort invested by the BriX collaboration in alpha decay studies in the Z=82 region, now firmly establishes a clear signature of the Z=82 closed shell in the alpha-decay probability, that has been looked for since many decades. The breakthrough comes from the understanding that the Po isotopes exhibit anomalous alpha decay properties, in contrast to Rn and Ra, because of their unusual ground state structure (that has now been clearly established via the in-source laser spectroscopy measurements and will be further studied using Coulex). These series of experiments have also revealed that one reaches the limit of the Geiger Nutall law, a text book example of quantum mechanical tunnelling through a potential barrier whereby a linear relation was found between the square root of the alpha decay Q-value and the log of its partial half life. We observed strong deviations from this linear behaviour and can explain them in terms of shell closures and multi-particle multi-hole excitations. Collaboration with the theory group from Stockholm (Sweden) who recently developed a more extended theory on alpha and cluster decay has been established.

Theory

In order to interpret these experimental findings theory efforts have been undertaken using symmetry based descriptions and beyond mean field approaches.

A description of shape coexistence was formulated, with particular emphasis on the Pb mass region, by means of a symmetry-dictated truncation to the nuclear shell model, i.e., the Interacting Boson Model. This research resulted in a number of papers on the appearance of collective intruder bands and their properties and the theoretical predictions formed an essential element in testing energy spectra, nuclear charge radii, transition matrix elements and, importantly, in proposing new experiments. Intensive work has been carried out to understand the way shape coexisting configurations, clearly observed in the Pb and Hg nuclei, propagate when moving away from the Z=82 closed shell. The Pt nuclei form a particular important series of isotopes in this respect. In collaboration with Huelva and Sevilla (Spain), an extensive

comparison between calculations, explicitly incorporating intruder configurations, with calculations, in which intruder configurations are not taken into account, was performed. In order to resolve this enigmatic situation, an extensive comparison of these two approaches has been carried out. Our recent study has shed new light on this transition and will be further explored.
Besides, a more general study of critical phenomena and phase transitions between different symmetry limits of the Interacting Boson Model (IBM),in particular the U(5)-O(6) and the U(5)-SU(3),O(6) transitions, has been carried out performed. Results have been published. Collective motion is most often studied using a geometrical framework. Using group-theoretical methods, a new algebraic approach (using the Cartan-Weyl basis) was developed allowing for a study of the spectral properties of collective Hamiltonians. This research has been published in three papers.

The beyond mean-field method that has been previously developed has been successfully applied to several nuclei in the vicinity of the neutron deficient Pb isotopes. The first step of this method is constituted by mean-field calculations with a Skyrme effective interaction and a constraint on the axial quadrupole moment. These mean-field wave functions are then projected on good angular momentum and particle numbers.
An application to ^{188}Pb, ^{186}Pb and ^{194}Po has been first performed in collaboration with a group of experimentalists from Jyväskylä and with the theory group of UGent. The determination of quadrupole transition probabilities and their comparison with the experimental data has enabled to analyse in details the large mixing of configurations that are obtained in these nuclei, in particular in Po which has a very soft dependence of energy as a function of the axial quadrupole deformation. The simultaneous application of our method and of the algebraic approach of the group from Gent has also permitted to confirm the importance of going beyond a single configuration description of these nuclei. The same group has extended their experiment to ^{196}Po. Our calculations allow interpreting the data as resulting from the mixing of the vibrational and rotational configurations at low spin. This work is actually complemented by a systematic application to neutron deficient nuclei from Pt (Z=78) to Rn (Z=86) which are actively studied experimentally with the BriX collaboration.
An application of the same method to the determination of the isotopic shifts in Pb isotopes has also been performed in the collaboration. Experimental results obtained at Isolde by the BriX network have shown that the isotopic shifts obtained for the lightest Pb isotopes do not follow the trend that is predicted for spherical nuclei by the liquid drop model. Our results have shown the great sensitivity of the isotopic shifts to the mixing of different configurations in the ground states.
The starting point of our method is an energy density functional (EDF), which is adjusted on a few key data and used without changes all over the nuclear chart. We have performed extensive studies in 2009 of the effect of tensor terms on deformations and on rotating nuclei. To study the effect of the tensor parameterization on deformation, we have performed a detailed analysis of the experimental data for semi magic nuclei and we have compared them to the theoretical results obtained with several tensor parameterizations. One of our conclusions is that other terms have to be included to the existing EDF to correct their actual deficiencies and that a tensor interaction is not sufficient.
We have also continued the study of the effect of a tensor interaction for nuclei breaking time reversal invariance (TRI), odd nuclei or rotating nuclei in the cranking approximation. The

breaking of time reversal invariance induces new terms in the EDF, arising from the central and from the tensor part of the interaction.

Main achievements and conclusion:

Mean square charge radii in Pb and Po isotopes and transition matrix elements in Hg isotopes have been determined and compared to state-of-the-art calculations. The interaction between normal and intruder states in the ground and excited states of these far neutron deficient nuclei has been established. These elements pave the road for a full understanding of the interplay between individual nucleon and collective behaviour in the atomic nucleus.

An asymmetric mode in the cold fission of ^{180}Hg was evidenced via a study of the BDF of ^{180}Tl. This totally unexpected aspect is believed to be due to subtle effects in the potential energy surface landscape around the saddle point.

Using a symmetry-dictated truncated shell-model approach (IBM), we can understand the changing shape coexisting structure, moving from Pb, through Hg into the Pt nuclei, through an increasing mixing between regular and particle-hole intruder configurations. The beyond mean-field method that we have developed has been validated by detailed studies performed on neutron deficient nuclei around the Pb isotopes and is ready to be applied on the recent results obtained on the Po isotopes. In parallel, our method has been generalized in order to correct the deficiencies that the comparison with the data has revealed.

4.4 Proof the presence of spin-alignment in relativistic U-fission at the FRS-GSI. Investigate the changing shell structure near the doubly-magic neutron-rich ^{132}Sn via moments measurements (KU Leuven – Köln – GSI – CSNSM)

A series of g-factor measurements was performed at the FRS-GSI fragment separator, within the g-RISING collaboration Three new isomers have been observed in the ^{125,127,129}Sn isotopes, completing the isomer systematics approaching the N=82 shell gap. The g-factor of microsecond isomeric states in ^{126}Sn, ^{127}Sn and ^{128}Sn support the tentatively assigned spins and configurations for these states. The g-factor of a sub-microsecond isomeric state in ^{194}Pb was re-measured and a significant amount of spin-alignment was observed. It was the first time that spin-alignment was observed in relativistic fission and fragmentation reactions producing intermediate and heavy isomeric beams, thus opening the way for isomeric moments studies on isotopes otherwise hard to orient.

Main achievements and conclusion:

Spin-alignment has been demonstrated in isomeric beams of heavy and intermediate mass isotopes produced by relativistic fission and fragmentation reactions at GSI, opening a window for moment studies on neutron-rich isomeric states that are not accessible by other methods.

Workpackage 5: Nuclei along the N=Z line

5.1 Mass measurements of N=Z nuclei (K.U.Leuven – GANIL - GSI)

In preparation of mass measurements using the SHIPTRAP set-up at GSI, we investigated possible ways to produce one of the most crucial nuclei in the region around ^{100}Sn, namely ^{94}Ag. This particular nucleus possesses two long-lived isomers of which the 21^+ isomer is believed to decay via one proton and possibly two-proton emission. Crucial in this study is to determine the exact location of these isomers. At the LISOL set-up we developed successfully a new ionization scheme for the Ag isotopes and tested it on-line using a heavy ion fusion evaporation reaction reaching as far out as ^{96}Ag (see item 5.3). We investigated the possibility to use this scheme to perform isomer selection and thus to obtain an isomeric purified beam that would be ideally suited for mass measurements and more detailed decay studies. Furthermore, these measurements would fix the spin and parity as well as indicate their degree of deformation. An efficient scheme for the Sn isotopes has been established as well in preparation of further studies at the S3 project (GANIL) (see WP 1). These developments have been started in 2009 and will continue in 2010 and 2011.

Deviation from the initial program:

As mentioned under WP 1 the activities within the BriX collaboration related to GSI have been focused on alpha-decay and BDF experiments at SHIP, the gas cell developments and the RISING campaigns. Furthermore, the mass measurements of the isomer in ^{94}Ag (one of the goals of the project) needed an extensive development of a proper laser ionization scheme that was only recently discovered. As a consequence mass measurements around ^{100}Sn using SHIPTRAP have not yet been initiated within the BriX network.

5.2 Theoretical studies along the N=Z line (UGent – ULB - GANIL)

A major improvement of the method that we have developed has been finalised: the simultaneous treatment of axial and non-axial quadrupole deformations and the breaking of time reversal invariance. Both developments should significantly improve our description of spectra and in particular correct for the overestimation of excitation energies that are obtained in deformed nuclei. The price to be paid is an increase of the computing times by at least an order of magnitude and a significant complication of the codes. However, this new tool should open an enormous range of new applications: odd nuclei, new excitation modes of even nuclei, improvement of the correlations that are taken into account for a systematic description of masses, etc. A test application to ^{24}Mg shows that the triaxial degree of freedom has indeed a significant effect on excitation energies. The method is satisfactorily working, but still requires further improvements to be systematically applicable to medium mass nuclei.
Mass differences are an often used signature and measure for shell closure. Using the angular-momentum projected Generator Coordinate Method, we have analyzed the modification of mass differences due to static deformation and dynamic fluctuations around the mean-field ground state. Looking at the shell closures where the S_{2N} values exhibit discontinuities, static mean-field deformations and dynamical correlations decrease systematically the amplitude of these gaps, and reduce them far from stability. Both effects are not related to a reduction of the spherical shell structure, which is usually invoked, but rather both underline the importance of fluctuations around single mean-field configurations for a high-precision description of nuclear masses. Our

systematic calculation shed a new light on the effect that is usually interpreted as due to the quenching of spherical shell gaps.

5.3 Beta-decay studies along the N=Z line (K.U.Leuven – GSI - GANIL)

Laser spectroscopy of ^{57}Cu

As mentioned in WP1, we proceeded to measure the hyperfine structure of the neutron-deficient copper isotopes ^{57}Cu and ^{59}Cu by means of in-gas-cell laser spectroscopy at LISOL, in order to extract their magnetic dipole moments; those had previously been measured by nuclear magnetic resonance but confirmation of those measurements was necessary. The two isotopes could be studied systematically to a great extent. The previous, very precise, measurement of the magnetic dipole moment of ^{59}Cu has been confirmed. In the case of ^{57}Cu, our result is in contradiction with the nuclear magnetic resonance measurement. The new result agrees with different large scale shell model calculations indicating that the ingredients to describe the nuclei around the Z=N=28 shell closure are well understood and implemented in the present models. The paper on these results was taken up by the American Physical Society in their “Physics: spotlighting exceptional research” section.

Laser spectroscopy of neutron-deficient Ag and Sn isotopes

A new laser ionization scheme for Ag was developed and used for a laser spectroscopy investigation of the $^{101-97}$Ag isotopes. The nuclei were produced in heavy ion fusion evaporation reactions at the LISOL facility. It should be possible to extract spin and parities as well as magnetic moments. The new laser scheme can give to a certain degree isomer selectivity and we are investigating new approaches to beta decay studies of these isomers. Further experiments are planned for 2010 and 2011.

Main achievements and conclusion:

The magnetic moment of 57Cu was measured and refuted the previous measurement. The agreement with the large-scale shell model calculations indicate that the ingredients necessary to describe the nuclei around the Z=N=28 shell closure are correctly implemented in the present models.

A new laser ionization scheme for Ag and Sn has been established allowing magnetic moment measurements down to the N=50 isotope ^{97}Ag. These developments are crucial for the S3 project (GANIL) and can be implemented in the SHIPTRAP set-up (GSI) to study even more exotic nuclei.

5.4 Improve the efficiency and sensitivity of the WITCH set-up (K.U.Leuven – GANIL - GSI)

The beam transport efficiency of the WITCH set-up was further improved. Over the last three years a gain of about a factor 100 was realized. Also, ion clouds of 10^4 to 10^5 ions can now be kept for up to several seconds in the Penning traps, without significant losses. Further, new Penning traps were installed providing a mass resolution of about 200.000. Analysis of the first measurement of a recoil ion energy spectrum with trapped ^{124}In has yielded the first physics results with WITCH, i.e. the charge state distribution of the ^{124}Sn recoil ions.

In the past two years several technical improvements of the WITCH set-up have been implemented:
- an ion source for stable Na, K and Cs beams was installed;
- a compact linear RFQ-trap to transform the beam from this ion source into bunches of several pA intensity was installed;
- a magnetic shield to limit the stray field of the WITCH magnet at the neighbouring REX-ISOLDE beam line was designed, constructed and installed. A further extension of this shield turned out to be necessary, which is currently being prepared.
With this shield, the ion source and the RFQ-trap in place the amount of time available for testing and optimizing the WITCH setup with stable beams will be enhanced significantly.
- simulations and measurements to better understand the creation of secondary ions in the set-up were performed;
- an unwanted Penning trap for electrons, caused by the specific electromagnetic field configuration in the WITCH the system and which led to the creation of secondary ions (by discharge ionization of rest gas) in turn causing an unwanted background in the recoil ion spectra, was localized and removed by the installation of an additional magnet;
- the vacuum system was upgraded: all non-UHV compatible materials were removed and a large amount of non-evaporative getter material as well as two getter pumps were installed. This has significantly increased the pumping speed. The vacuum has improved by more than an order of magnitude to about 5 x 10^{-9} mbar, with a vacuum in the 10^{-10} mbar region being feasible after bake-out.

5.5 Optimise the determination of the beta-asymmetry parameter and obtain improved precision (K.U.Leuven – CSNSM)

A Geant 4 Monte Carlo simulation code for beta-asymmetry parameter measurements was developed and optimized, especially with respect to the effects of scattering and of the magnetic field. This code is also used to identify and quantify different types of systematic effects. Further, the operational characteristics of Si PIN diodes for particle detection at 10K and in magnetic fields up to 11 T were investigated in detail. Finally, a new type of data acquisition system was tested as well, with good results.

5.6 Weak interaction studies using the WITCH spectrometer and low-temperature nuclear orientation devices (K.U.Leuven – GANIL - CSNSM)

Two beta asymmetry parameter measurements using low-temperature nuclear orientation were performed with ^{60}Co and ^{114}In. The above mentioned Monte Carlo code was used in the analysis of these experiments. For ^{60}Co a relative precision of 2.0% was achieved for the beta asymmetry parameter, while the measurement with ^{114}In has yielded a precision of 1.4%. This is the most accurate result for the beta asymmetry parameter in nuclear transitions ever achieved. Both results provide new information on a possible tensor contribution to the weak interaction. A new measurement was in the mean time performed as well, using ^{67}Cu at ISOLDE-CERN. These data are being analyzed.
Finally, we have analysed - in collaboration with I.S. Towner (Texas A&M Univ., USA) – the corrected Ft-values for the T = 1/2 mirror transitions up to ^{43}Ti, including the radiative and nuclear structure related corrections, similar to the superallowed $0^+ \rightarrow 0^+$ transitions. This was

published in Phys. Rev. C. These Ft-values are necessary to interpret ongoing and future correlation measurements with mirror nuclei to search for physics beyond the standard model.

Main achievements in relation to initial objectives:

The efficiency and sensitivity of the WITCH set-up has been improved by at least two orders of magnitude. The system is now ready to produce first physics results. The method to determine the beta-asymmetry parameter was improved as well, leading to the currently most accurate result for this parameter in nuclear beta decay and providing new information on a possible tensor type charged current weak interaction.

Workpackage 6: Structure and reactivity of rare actinides

6.1 Structure and reactivity of rare actinides, experimental determination of the Cm(n,f) cross section (SCK•CEN, UGent, ULB, CSNSM)

Experimental study

In order to determine the thermal neutron induced fission cross section of the Cm isotopes a dedicated experimental setup was installed at one of the irradiation channels of BR1, including neutron beam optimization and characterization.

A first series of measurements at BR1 was performed in order to determine the thermal neutron induced ^{247}Cm(n,f) cross section. For this purpose a highly enriched ^{247}Cm target was mounted in the ionization chamber. The measurement results showed a degraded fission spectrum, indicating that the ^{247}Cm sample is crystallized and is therefore not suited anymore for an accurate cross section measurement. Another (anticipated) difficulty was the alpha pile-up due to spontaneous alpha-decay (mainly from ^{244}Cm impurities). The alpha count rate recorded with the ionization chamber was about 5×10^5 s^{-1}, which was at the operational limit of the detector.

A second series of measurements at BR1 focussed on the ^{245}Cm(n,f) reaction. As the alpha count rate due to spontaneous decay was expected to be about five times higher than with the ^{247}Cm sample, a faster detection system was consisting of PIPS detectors mounted in a vacuum chamber. A complete measurement campaign was executed, including background measurements to correct for spontaneous fission and for epithermal neutron induced fission. A preliminary thermal neutron induced ^{245}Cm(n,f) cross section value has been obtained. The final result will be determined and published when the Westcott factor g_f deduced from the measurements at IRMM is available (see further). The possibility of improving the accuracy on the target characterization is being investigated.

Another experimental campaign at BR1 was started to determine the ^{243}Cm(n,f) cross section. The same setup as for the ^{245}Cm sample was used for these measurements. A preliminary value has been determined but the measurements are still ongoing in order to improve the accuracy.

In order to include the Westcott factors in the analyses of the thermal neutron induced cross section measurements at BR1, knowledge of the neutron temperature is required. For this purpose, a set of thermocouples was introduced inside the BR1 irradiation channel that is used for the Cm(n,f) measurements. In this way the graphite (moderator) temperature in the centre of this channel is recorded during the measurements.

Measurements of the $^{245}Cm(n,f)$ cross section have been performed at the GELINA neutron time of flight facility of the Institute for Reference Materials and Measurements (IRMM) in Geel. Two 3000 mm^2 large silicon surface barrier detectors were positioned in a vacuum chamber on both sides of back-to-back mounted ^{245}Cm – ^{10}B samples. One was used for the detection of the fission fragments, the second detected the $^{10}B(n,\alpha)$ particles needed for the determination of the neutron flux. The chamber was placed in the neutron beam at a 9 meter long flight path.
A calibration experiment based on the well known $^{235}U(n,f)$ cross section has been performed to validate the experimental setup and the data reduction program.
A first measurement of the $^{245}Cm(n,f)$ cross section has been done in the sub-thermal and thermal neutron energy region, GELINA being operated at a repetition frequency of 50 Hz. The main goal of this measurement is to obtain a more accurate Westcott factor (g_f) needed to improve the accuracy of the measurements at the BR1 reactor (the evaluated g_f factor has an uncertainty of 3%).
Consequently measurements have been performed in the $^{245}Cm(n,f)$ resonance region, GELINA being operated at a repetition frequency of 800 Hz. Partial results have been presented at a conference. The analysis of all available data is ongoing. Depending on sample availability the possibility of performing (n,f) measurements on other Cm nuclides is being investigated.

Theoretical study
To assess the predictive power of our method and the range of validity of the present effective nucleon-nucleon interactions, we have continued our systematic studies of quasi-particle excitations in nuclei around the No isotopes (Z=102). There is indeed an intense experimental activity in this mass region and these excitations are very sensitive to the single-particle properties predicted by mean-field methods. A very satisfactory agreement is obtained for most odd nuclei in this mass region (one quasi-particle excitations). On the contrary, there are strong discrepancies obtained by our calculations but also by calculations based on other families of effective interactions for isomeric states based on two-quasi-particle excitations in even nuclei.
The rotational structure of ^{255}Lr has been investigated in collaboration with a group of Jyväskylä. This nucleus is the heaviest element for which there is rich information on the low energy spectrum. Our calculation has permitted to assign a configuration to the rotational band detected up to a spin around 20 hbar.

Main achievements and conclusion:
A new set-up to measure precisely the $^{A}Cm(n,f)$ cross section was constructed at the BR1 reactor. Preliminary results were obtained. Final results for the thermal neutron induced $^{243}Cm(n,f)$ and $^{245}Cm(n,f)$ cross sections and for the $^{245}Cm(n,f)$ cross section as a function of the neutron energy will be obtained and published in 2010-2011.

Workpackage 7: Physics with intense proton beams

7.1 Feasibility/exploratory study of an irradiation station with 5/2.5 mA protons at 350/600 MeV, opportunities for Belgian fundamental research on radioactive nuclei on the long term (SCK•CEN, K.U.Leuven, UGent, ULB - Köln)

The development of the MYRRHA accelerator driven system is one of the main activities at SCK•CEN. In this work package the feasibility of using the high power proton beam that will become available in the MYRRHA accelerator driven system for fundamental research was investigated.
In order to have a global overview of existing large-scale proton facilities and research programs, workshop "Nuclear Physics Research at the MYRRHA accelerator" was organised on 7-8 April 2008, in combination with the annual BriX network meeting. This two-day workshop was hosted by SCK•CEN and organized by the BriX network partners. About 50 people participated to the workshop. The program of the workshop can be downloaded from the BriX website (http://iks32.fys.kuleuven.be/wiki/brix/index.php/Main_Page).
In the first session, an overview of the most important large scale proton facilities was presented. This session ended with a presentation of the MYRRHA facility, with special emphasis on the accelerator and the spallation target. The second session started with a presentation on the possibility of an ISOL (Isotope Separator OnLine) facility at MYRRHA and the beams that might become available. The rest of this session focused on research programs at existing facilities. The workshop was concluded with a round-up and a round-table discussion.
From the round-table discussion it was concluded that the installation of an ISOL system at the MYRRHA accelerator, called ISOL@MYRRHA, that focuses on experiments that need long beam time would offer unique research opportunities that are complementary with existing radioactive ion beam facilities. A working group within the BriX collaboration was established to perform a feasibility study and to produce an report on the technical and research opportunities of ISOL@MYRRHA. The working group came to the conclusion that a rich variety of research opportunities are potentially present for experiments which:

- need very high statistics;
- need many time-consuming systematic measurements;
- hunt for very rare events;
- have an inherent limited detection efficiency

These projects cover a variety of research fields including fundamental interaction studies, nuclear physics, condensed-matter studies, nuclear medicine.
The report entitled “ISOL@MYRRHA: An On-Line Isotope Separator coupled to the MYRHHA Proton Accelerator” is attached. Th report has been presented to the community at a number of conferences and has been submitted to the different working groups of the NuPECC Long Range Plan 2010 exercise for consideration.
In March 2010, the Belgian federal government has committed itself to financing 40% of the total investment for MYRRHA. The remainder needs to be financed by an international consortium, that has to be set up in the coming years. MYRRHA is foreseen to be fully operational by 2024. It has been decided by SCK•CEN management that delivery of the proton bundle for ISOL@MYRRHA is an integral part of the MYRRHA project.

<u>Major achievement and conclusion:</u>
An appealing physics case has been made for fundamental research using (part of) the proton beam from the MYRRHA project. An extensive report on the technical issues and the physics opportunities has been produced. The case has been favorably welcomed by the international community.

The High Intensity High Energy ISOLDE (HIE-ISOLDE) project

The BriX network is deeply involved in HIE-ISOLDE whereby the energy of the current ISOLDE beams will be boosted up to 10 MeV/u and the radioactive beam intensity will be increased by at least a factor of 5. The network was involved in the design and construction of the HIE-ISOLDE program as well as in establishing its physics case. The network has contributed financially as well as with man power to this project. A network collaborator, stationed at CERN, led the design and testing of the super conducting cavity prototypes at CERN. The coating tests have been successful and the first RF tests are underway. The network is also involved in the intensity upgrade of HIE-ISOLDE through the laser ion source and RF-cooler developments. The project has now been approved by the CERN research board and will deliver its first beams at 5 MeV/u in 2013. The HIE-ISOLDE project will be an essential part of the future of Belgian nuclear physics research in the short and mid-term future.

Instrumentation

As mentioned in the original proposal the following instrumentation was planned to be constructed or upgraded. The status is given below.

1. Miniball detector array:

A new set-up called T-REX consisting of a 4π silicon detector array was designed and constructed and put inside the Miniball array. It was successfully used for the transfer reactions and will in a later stage also be used for the Coulomb excitation measurements (WP 3, 4 and 5)

2. New beta-decay set-up

A new beta-decay detection set-up based on two highly shielded Miniball germanium detector triples, 50% of 4p plastic detectors and a fast moving tape system was constructed and used for experiments at LISOL and ISOLDE (WP 3, 4 and 5)

3. A spectrometer for experiments at HIE-ISOLDE in combination with MINIBALL

This program has encountered a delay as the HIE-ISOLDE project (a project to accelerate the ISOLDE beams to 10 MeV/u and to increase the radioactive beam intensity in some case by an order of magnitude) has only recently been approved by the CERN management (December 2009). Now that the HIE ISOLDE project launched the separator/spectrometer design/construction program has been taken up again. Part of the “MINIBALL workshop and user meeting (Leuven, Belgium, April 15 – 16, 2010)”, organized by the BriX partners, was dedicated to letters of intent for HIE-ISOLDE and to a initial discussion on the new instrumentation for HIE-ISOLDE, including a separator/spectrometer. A dedicated workshop in this issue will be organized by CERN after an evaluation of the LOI’s is performed by the CERN-ISOLDE committee.

4. *The detection systems for WITCH and for the beta-asymmetry measurements*
See report in WP 1.3

5. *A set-up for measuring thermal neutron fission cross sections of exotic nuclei at the BR1 reactor in Mol.*
See report in WP 6.1

General conclusion on the research results:

As evidenced by the publications and the short status reports given above, the BriX collaboration has achieved or is on its way to achieve its major scientific goals as described in the original proposal. This success is based on a well balanced mix between theoretical and experimental work, the latter mainly performed at the major European radioactive ion beam facilities like ISOLDE-CERN, GANIL and GSI using state-of-the-art instrumentation (laser systems, highly segmented germanium and silicon detectors, ion traps). The scientific output gives the members of the BriX collaboration an international visibility. A strong physics case for radioactive ion beam research using the recently approved MYRRHA project has been worked out. Building further on these achievements and combining them with the interesting opportunities that will result from the recently approved HIE-ISOLDE project and MYRRHA projects, and from the SPIRAL-2 and FAIR projects (under construction), will create unprecedented opportunities for nuclear physics research in Belgium.

3. NETWORKING

The BriX network involves experimental nuclear physics groups from the universities of Leuven (K.U.Leuven), Gent (UGent) and Mol (SCK•CEN), and theoretical groups from the universities of Brussels (ULB) together with the European partners GANIL (France), GSI (Germany), IKP – U.Köln (Köln) and CSNSM (Orsay). An intense collaboration with ISOLDE-CERN (Switzerland) exists as well. During the numerous experimental campaigns at ISOLDE-CERN, GANIL, GSI and at the Orsay tandem accelerator contacts between the different members of the BriX network are established.

Apart from the research performed within the groups, an intense networking activity is developed that results in a number of joint publications (see list of “co-publications”), research projects and applications for beam time and funding. This networking activities ranged from formal contacts during steering committee meetings to informal contacts between the PhD students, post-docs and staff of the network during the BriX workshops, joined experiments and international meetings, schools, workshops and conferences. Different partners of the network are also involved in the organization of common workshops and schools. A wiki based webpage was set up to post the annual reports, the talks of the IAP BriX days and relevant announcement. Every collaborator had the possibility to work on the web page. However, daily practice showed that other platforms for contacts between the BriX collaborators as mentioned above, were used much more effective. As a result the website has in essence only be used to download and consult talks and presentations of the IAP BriX days and the ISOL@MYRRHA report.

The added value of the network results from the interesting mix between experimental and theoretical groups, the intensive contact with the three major radioactive ion beam facilities in Europe (GANIL, GSI and ISOLDE) and the research groups from CSNSM and U.Köln with their specific know-how (e.g. on the instrumentation side: the in-flight polarization technique and germanium detector systems). This resulted in a number of joint publications (see list in addendum) but also several new experiments have been proposed based on discussion between the experimental groups and the theory groups and with the EU partners from the network. The laser spectroscopy and Coulomb excitation study on the polonium isotopes, the Coulomb excitation on the Hg isotopes, the decay study of the Mn isotopes, the collinear laser spectroscopy on the Cu isotopes, the WITCH project at ISOLDE, the BDF study at GSI and at ISOLDE, the gas cell based laser ion source for S3 and the study of the ground state properties of the N=28 isotopes at GANIL are only a few examples (see a more extended list below). As a typical example, we can quote the BDF study of ^{180}Tl, where the surprising asymmetric mass distribution was observed. This study was initiated from the observation of BDF decay in the neutron deficient isotopes around Z=82 at GSI by the Leuven group, and followed by a campaign at ISOLDE using the know-how and expertise on fission from the UGent and SCK•CEN partners, while the final interpretation of the data will involve fission barriers that will be calculated by the ULB partner.
Working out the technical and physics case for the ISOL@MYRRHA project and writing a white paper on this challenging project was an international undertaking with involvement of essentially all partners of the BriX network. Important to note is that this exercise that creates

unique opportunities for state-of-the-art nuclear-physics research in Belgium has been initiated and made possible thanks to the network and the participation of the SCK•CEN partner in it. This initiative was for example also the catalyst for a new collaboration agreement between K.U.Leuven and SCK•CEN that was signed in 2009 to initiate common research projects not only in the above mentioned field but also in applied, biomedical and human sciences. Similar agreements between SCK•CEN, UGent, and ULB are under consideration.
Different partners of the network were involved in the Integrated Infrastructure Initiative EURONS (leading and participating e.g. in a number of Joint Research Activities) and are involved in the new Integrated Infrastructure Initiative ENSAR that is under contract negotiation with the EU. This was only possible thanks to the intensive networking activity within the BriX network.
Finally, we wish to mention that the next "flag ship' conference in the field of radioactive ion beam research, the so-called "International Conference on Advances in Radioactive Isotope Science: ARIS-2011 (iks32.fys.kuleuven.be/aris) will be jointly organized in Belgium in 2011 by K.U.Leuven and ULB (see also 4.2). Again this is a result of the intense networking between these two partners resulting from the BriX activities.

Below we list some of the joint activities that resulted from the BriX network.

3.1 Meetings and workshops
Apart from the seminars and specific discussion meetings between the different partners, a number of workshops and schools were organized (partly) in the framework of the BriX network. These workshops and schools are listed below:

- "IAP - BriX day"
January 23, 2007, Leuven, Belgium
- International workshop "g−RISING: kick−off meeting"
June, 5−6, 2007, Sofia, Bulgaria
- "Euroschool on Exotic Beams"
August 26 – 31, 2007, Houlgate, France
- "Seminar on Fission VI"
Corsendonk Priory, Belgium, 18-21 September 2007
- "Exploratory visit: opportunities for Flemish nuclear physics research at the ILL"
Institut Laue-Langevin, Grenoble, 22-23 October 2007
- "Nuclear Many-Body approximations for the 21st century"
INT, Seattle, from September 24 until November 30,2007
- "ISOLDE Workshop and Users Meeting"
December 17 - 19, 2007, CERN, Geneva, Switzerland
- "Nuclear Physics Research at the MYRRHA accelerator"
April 7-8 , 2008, SCK•CEN, Mol, Belgium
- "IAP - BriX day"
April 9, 2008, SCK•CEN, Mol, Belgium
- "WITCH Collaboration meeting"
June 23-24, 2008, Leuven, Belgium
- "Euroschool on Exotic Beams"

September 1 – 6, 2008, Piaski, Poland
- Joint LASER – TRAPSPEC workshop
September 28 – October 1, 2008, La Londe des Maures, France
- "ISOLDE Workshop and Users Meeting"
November 17 – 19, 2008, CERN, Geneva, Switzerland
- Miniball workshop and users meeting
December 8 – 10, 2008, München, Germany
- "Nuclear structure in the neutron−rich region around Z=28, towards and beyond N=50"
March 9−11, 2009, Leuven, Belgium
- "WITCH Collaboration meeting"
May 18-19, 2009, Münster, Germany
- "Euroschool on Exotic Beams"
September 4-11, 2009, Leuven, Belgium
- "Seminar on Fission VII"
May 16-20, 2010, Het Pand, Gent, Belgium
- XVI ieme Colloque GANIL 2009
September 6−11, 2009, Giens, France
- "WITCH Collaboration meeting"
March 1-2, 2010, Leuven, Belgium
- MINIBALL workshop and users meeting
April 15-16, 2010, Leuven, Belgium

3.2 Exchange of equipment and data, and joint experiments

- Equipment, know-how and data have been exchanged between the different partners of the network. Below we give a brief summary of the most important exchange actions:

- A magnet from K.U. Leuven has been installed at GSI for measurements of g-factors (experiments S308, S310, S311).
- The new set-up for beta-decay studies (developed at K.U.Leuven) has been used at LISOL and ISOLDE (collaboration SCK and K.U.Leuven). The data has been exchanged between the different partners.
- The windmill system for alpha and BDF studies (developed at K.U.Leuven) has been used for measurements at ISOLDE (collaboration UGent, K.U.Leuven and GSI). The data has been exchanged between the different partners.
- An experimental set-up to perform β-NMR and β-NQR experiments has been developed at Leuven and installed at GANIL for experiments E437b and E513a.
- The WITCH set-up, permanently installed at ISOLDE, is used in a large international collaboration including members of the BriX network (K.U.Leuven, GSI)
- The MINIBALL detector system is used in a large international collaboration including members fo the BriX network (K.U.Leuven, UGent, U.Köln, CSNSM, GANIL, GSI, SCK). The data has been exchanged between the different partners.
- The LISOL laser system and gas cell has been used for feasibility studies for the S3-SPIRAL-2 (GANIL) project (K.U.Leuven, GANIL)
- Data of the experiment S311 at GSI had been analysed at U.Köln in collaboration with K.U. Leuven.

- Exchange of an acquisition system, ionisation chamber and part of the electronics material between SCK•CEN and UGent.
- Exchange of data on the Cu Coulex between K.U.Leuven and CSNSM has been established.
- Exchange of data on the Po laser spectroscopy between K.U.Leuven, Mainz and ISOLDE has been established.
- Exchange of know-how on the analysis of the fission fragments emitted in β-delayed fission of ^{180}Hg between K.U.Leuven and UGent.
- Exchange of data on the beta decay of neutron-rich Cu isotopes between K.U.Leuven and GANIL
- Exchange of know-how on segmented Ge detectors between U.Köln and K.U.Leuven
- Exchange of know-how on the analysis of Coulomb excitation data between K.U.Leuven, U.Köln, GANIL and CSNSM
- Exchange of know-how and expertise on the ACTAR (active target for reaction studies) between K.U.Leuven and GANIL

- Several joined experiments took place with the BriX collaboration. Below a brief list of the major campaigns (e.g. with BriX members as spokesperson or one of the leading laboratory) is given. Apart from this list, BriX partners are involved in a number of other experiments as participating collaborator

GANIL (partners: K.U. Leuven – UGent - GANIL)
E437b: Measurement of the ground state quadrupole moments of ^{31,33,34}Al
E513a: Study of neutron rich N~28 isotopes: ground-state spins and nuclear magnetic moments of $^{41\text{-}45}$Cl and ^{43}S
E384a: Quadrupole moment of $9/2^{+}$ isomer in ^{61}Fe

ISOLDE (partners: K.U. Leuven– UGent – ULB - SCK•CEN – U.Köln – CSNSM - GSI - GANIL)
<u>Laser spectroscopy</u>
IS427: Nuclear moments and charge radii of Mg isotopes from N=8 up to (and beyond) N=20
IS439: High-resolution laser spectroscopy of ground and excited nuclear states in neutron rich copper isotopes
IS449: Measurement of the isotope shift of ^{7,9,10,11}Be at COLLAPS – A test for IS449
IS457: Laser spectroscopy of gallium isotopes using the ISCOOL RFQ cooler
IS480: Charge radii of magnesium isotopes by laser spectroscopy: a structural study over the sd shell
IS484: Ground-state properties of K-isotopes from laser and β-NMR spectroscopy

<u>Miniball (decay, Coulex and transfer):</u>
IS412: Coulomb excitation of neutron-rich nuclei between the N=40 and N=50 shell gaps using REX-ISOLDE and the Ge MINIBALL array
IS435: Coulomb Excitation of Odd-Mass and Odd-Odd Cu Isotopes Using REX-ISOLDE and Miniball
IS452: Measurements of shape co-existence in ^{182,184}Hg using Coulomb excitation
IS455: Investigation of alpha-decay rates of ^{221}Fr, ^{224}Ra and ^{226}Ra in different environments

IS456: Study of polonium isotopes ground state properties by simultaneous atomic- and nuclear-spectroscopy
IS466: Identification and Systematical Studies of the Electron-capture delayed Fission (BDF) in the Lead Region. Part I: BDF of ^{178,180}Tl and ^{200,202}Fr isotopes
IS467: Beta-decay Studies of Neutron rich $^{61\text{-}70}$Mn Isotopes with the new LISOL beta-decay setup
IS468: Investigation of Beam Purity after in-trap Decay and Coulomb Excitation of ^{62}Mn-^{62}Fe
IS469: One Nucleon Transfer Reactions Around ^{68}Ni at REX-ISOLDE
IS479: Shape coexistence measurements in even-even neutron-deficient Polonium isotopes by Coulomb excitation, using REX-ISOLDE and the Ge MINIBALL array.

Fundamental interaction studies:
IS431: Beta-Asymmetry Measurements in Nuclear Beta-Decay as a Probe for Non-Standard Model Physics
IS433: Search for new Physics in Beta-Neutrino Correlations using Trapped Ions and a Retardation Spectrometer

GSI: (partners: K.U. Leuven – GSI – CSNSM – U.Köln)
S308: g-factor of isomeric states in Pb-region from U fragmentation
S310: g-factor of isomeric states near ^{100}Sn
S311: g-factors and spin-alignment of isomeric states near ^{132}Sn produced by U-fission
U245: Identification and systematic studies of the electron-capture delayed fission (BDF) in the lead region

3.3 Exchange of personnel

As mentioned in the annual reports 2007 and 2008, a healthy exchange of post-docs took place. We do not repeat here these details but instead focus on those persons who worked within the BriX network (Belgian partners only) and obtained a permanent research or professor position as this reflects to a certain extend the international visibility and success of the network (see also 5.3):

- R. Raabe (post-doc K.U.Leuven): obtained a permanent position at GANIL in 2008 but returned to K.U.Leuven where he became professor in nuclear reaction physics (Belgium)
- S. Rombouts (post-doc UGent): associate professor at University of Aarhus (Denmark)
- N. Smirnova (post-doc UGent and K.U.Leuven) took up a permanent position as 'Maitre de Conférences' at the 'Université de Bordeaux' (France)
- B. Bastin (post-doc GANIL and K.U.Leuven) obtained a permanent position at GANIL (France)
- N. Patronis (post-doc K.U.Leuven) obtained a permanent position at the Ionnannina University (Greece)
- L. Popescu (PhD student UGent, post-doc SCK•CEN) obtained a permanent position at SCK•CEN (Belgium)
- J. Van de Walle (PhD student K.U.Leuven, post-doc ISOLDE) obtained a permanent position at KVI – Groningen (The Netherlands)
- A. Andreyev (post-doc K.U.Leuven) obtained a professorship at the university of Paisley (U.K.)

- M. Bender (post-doc ULB) obtained a permanent research position at CENBG (Bordeaux, France) as “Directeur de Recherche”
- M. Venhart (post-doc K.U.Leuven) will obtain a permanent position at the university of Bratislava (Slowakia)

Exchange of staff for teaching on the master level
- Staff from the ULB (S. Goriely and P.H. Heenen) and of UGent (K. Heyde) are teaching specialized nuclear physics and astrophysics courses in the ‘Master of physics’ trajectory of “physics on femtometer scale: nuclear physics” at the K.U. Leuven.
- Staff from K.U.Leuven (N. Severijns) is teaching an experimental nuclear physics instrumentation course at ULB

4. Position of the IAP Network

4.1 Cutting-edge research

- **Scientific highlights**

The scientific highlights of the network can be summarized as:

- *Light nuclei*

- The beta delayed charge particle emission of a number of light nuclei (e.g. ^{11}Li and ^{11}Be, ^{8}B,..) has been determined to the lowest energy and the highest accuracy using a new experimental method developed within the BriX collaboration. These data confirm the predictions by state-of-the-art calculations. New reaction models have been developed for low- and intermediate energy with a special attention to continuum states, which play a crucial role in exotic nuclei.

- *The N=20 shell closure: the island of inversion*

- The preliminary value of the ^{33}Al ground state quadrupole moment measured with a new dedicated multiple-rf NQR set-up for polarized fragment beams at GANIL, revealed for the first time a very clear signature of intruder components in its ground state wave function, thus extending the region of the 'island of inversion' towards the Al isotopes. This information was complemented with one and two-neutron transfer reaction data on ^{30}Mg identifying intruder and normal state around N=20. These data constitute a testing ground for beyond mean-field calculations and shell-model calculations.

- *The region around the doubly magic ^{78}Ni (Z=28, N=50)*

- The ground state spin, magnetic and quadrupole moments of the very exotic neutron-rich Cu and Ga isotopes have been measured in a model-independent way using co-linear laser spectroscopy and with high precision using the newly-installed ISCOOL ion cooler/buncher at ISOLDE. These experiments evidences an abrupt change in the ground-state spin and parity in ^{73}Ga and in ^{75}Cu and solidly proof the expectations that were raised from beta decay study that were performed with the BriX network during one of the previous phases.
- Coulomb excitation experiments were performed on the neutron-rich Cu and Zn isotopes (including isomers using) and evidenced a strongly excited collective low-lying structure in the Cu isotopes as well as a weakly excited high-lying 2^+ in ^{80}Zn (N=50).
- The resonant laser ionization allowed the production of isomeric radioactive ion beams. These beams were used for Coulomb excitation measurements. The production and use of a post-accelerated isomeric beam was a world premiere. Excellent data were obtained on the ^{66}Ni(d,p) reaction. These results shed light on the fragility of the N=40 neutron sub-shell closure.
- These data are now compared with different theoretical shell-model descriptions and form a stringent test of the interactions used around ^{78}Ni.

- *Fundamental interaction studies*

- The efficiency and sensitivity of the WITCH setup to search for new types of weak interaction not included in the Standard Model, has been improved by at least two orders of magnitude and the system is now ready to produce first physics results.

- The measurement of the beta asymmetry parameter in the decay of ^{114}In constitutes the most accurate and most precise result ever achieved for this parameter in a nuclear beta transition. Together with the almost equally precise result from a similar measurement with ^{60}Co it provides new information on a possible tensor type charged current weak interaction.

- *The Z=82 closed proton shell: shape coexistence*

- In-source laser spectroscopy measurements in the Pb and Po isotopes unambiguously show that the Pb isotopes stay essentially spherical in their ground state (no need for a breaking of the Z=82 closed proton shell) while the Po isotopes become increasingly collective when going towards the N=104 mid-shell region. Coulomb excitation experiments were performed on the neutron-deficient Hg and Po isotopes. Although still under analysis, these data will give, for the first time, quantitative information on the mixing between the normal and intruder states and on the size and sign of the quadrupole deformation. Symmetry based and mean field based calculations performed within the collaboration have been and will be compared with experiment and indicated the true nature of the shape coexisting structures.

- *Development of the in-source gas cell based laser ionization*

The very sensitive technique of in-source laser spectroscopy has been extended to gas cell systems allowing now the study of refractory type elements, a class of radioactive isotopes that can not be studied at high-temperature based ISOL systems. A new result on the magnetic moment of ^{57}Cu was obtained refuting the previous measurement and in agreement with the large-scale shell model calculations.

- *A physics case for ISOL@MYRRHA*

Interesting physics cases for an ISOL system coupled to the proton beam of the MYRRHA project, so-called ISOL@MYRRHA, have been identified and worked out, resulting in a complementary research program tailored to challenging experiments that need very long beam time. The proposed research is not limited to nuclear physics and fundamental interaction studies, but includes opportunities for atomic physics, condensed matter and biomedical research and applications. The full report is attached.

- *Theory*

We have developed a wide variety of reaction models, ranging from low energies to intermediate energies. Recent improvements have focussed on the projectile wave functions (multicluster models, microscopic models), and on the reaction description (CDCC, Eikonal, semi-classical). Several processes have been considered: elastic scattering, breakup, radiative capture. Special attention has been paid on continuum states, which play a crucial role in exotic nuclei, owing to the low separation energies. The theoretical structure models that are developed within the collaboration have been extended and their validity has been assessed by numerous confrontations with data. Symmetries have been broken in the beyond mean-field approach in order to include the description of nuclei with an odd number of neutrons or protons. Extensions of the energy density functional have been proposed (and are still studied) to correct the main deficiencies encountered in the confrontation of experimental data. We have furthermore presented a quantitative study of the role played by different components characterizing the nucleon-nucleon interaction in the evolution of the nuclear shell structure. This is based on a

spin-tensor decomposition of an effective two-body shell-model interaction and allowed us to separate unambiguously contributions of the central, vector and tensor components of the realistic effective interaction. We have shown that while the global variation of the single-particle energies is due to the central component of the effective interaction, the characteristic behaviour of spin-orbit partners is mainly due to its tensor part. In particular we have analyzed in detail the role played by the different terms in the formation and/or disappearance of N=16, N=20 and N=28 shell gaps in neutron-rich nuclei. A new method to study the spectral properties of a tractable collective model has been proposed. Truncating the potential energy up to quadratic terms in the quadrupole deformation variables allows us to incorporate vibrational, γ-independent rotational, and axially deformed rotational structures. These physically significant limits were analysed in detail and confronted with well-established approximation schemes. Furthermore, transitional Hamiltonians in between the limits are presented and discussed. All results are obtained within a recently presented Cartan-Weyl based framework to calculate SU(1,1)xSO(5) embedding quadrupole collective variables.

- **Position of the BriX program within the mainstream**

The Brix research program focuses on a limited number of theoretical and experimental key issues that were chosen on the basis of the expertise present within the network, the possibilities for radioactive ion beam research (mainly in Europe) and last but not least on its importance in progressing the understanding of the strong and weak interaction at play in the atomic nucleus. The experimental part of the program covers activities in the field of radioactive ion beam production (laser ionization), decay studies, moment measurements and reaction studies with radioactive beams and/or targets. The development of instrumentation (e.g. segmented detector systems, lasers, ion traps and ion manipulation systems) forms an integral part of the activity. Theory concentrates on shell-model and symmetry-based descriptions and beyond mean field approaches to describe the nuclear structure and on reaction models tailored to exotic nuclei research emphasizing weakly or unbound systems. Essentially all these activities are embedded in larger international collaborations, where the Belgian partners often take up a leading role. The NuPECC and also NSAC Long Range Plan exercises came to the conclusion that research with radioactive ion beams is one of the most important research fields in contemporary nuclear physics as it is expected that the outcome of this research will trigger major steps forward in our understanding of the atomic nuclei. The BriX research program is fully in line with the recommendations and the ISOL@MYRRHA project is regarded favorably by the international community.

- **Future perspectives**

The future perspectives of nuclear-physics research in Europe is currently under evaluation by the community through the NuPECC 2010 Long Range Plan exercise. Several staff members of the BriX network are members or conveners of the different working groups that are preparing the long range plan. These working groups cover the following themes: QCD, Phases of Nuclear Matter, Nuclear Structure, Nuclei in the Universe, Fundamental Interactions, Applications of Nuclear Science. The last four groups cover themes of the BriX network and members of the

network participate in these brainstorming activities. The final report and recommendations have to be discussed at the town meeting in Madrid (May 2010). But it is already clear from the preliminary versions of the text and the numerous preparatory workshops and meetings that the field of radioactive ion science will continue to be one of the main priorities in Europe for the coming 10 to 20 years. The research will be driven by the major infrastructures that are under construction in Europe: FAIR at GSI-Darmstadt (Germany), SPIRAL-2 at GANIL-Caen (France), HIE-ISOLDE at CERN (Switzerland) and SPES at Legnaro (Italy). The activities that will be undertaken at these facilities and the participating institutes and universities will guide our research. Furthermore the approval of the MYRRHA project and the plans to construct and ISOL@MYRRHA system at Mol (Belgium) is considered as an important milestone for the fundamental and applied nuclear-physics research. The U.S.A. (NSAC long range plan), Canadian (the upgrade plans for TRIUMF-Canada) and Japanese (the Radioactive Ion Beam Factory at RIKEN) nuclear physics communities came to the same conclusion as described above. The research activities developed by the BriX network allows Belgian research groups to take up a visible and leading role in the mid- and long-term radioactive isotope science programs in Europe.

The network's expertise is internationally recognized. This is evidenced by several items:
- numerous invited talks at international conferences and workshops by members of the network
- membership of international advisory boards of accelerator facilities (Europe: ISOLDE-CERN-Switzerland, JYFL-Finland, LNS-Italy, ILL-France, GANIL-France, U.S.A.: NSCL – MSU, ANL – ATLAS, Japan: RIKEN)
- membership of evaluation committee of research institutes (LPSC Grenoble-France, GSI Darmstadt-Germany, CENG Bordeaux-France)
- membership of evaluation committees of several national funding organizations (FWO and FRNS - Belgium, DFG-Germany, ISF-Israel, NSERC-Canada, The Netherlands, France, U.K.)
- member of editorial board of e.g. Physical Review C and acting as divisional associated editor of Physical Review Letters and of the Nuclear Physics Board of the European Physical Society.
- strong involvement in NuPECC's working groups for the Long Range Plan 2010 exercise.
- involvement in major international collaborations (MINIBALL, COLLAPS, nEDM, WITCH, NUPNET,…)

4.2 International role

A. Collaboration with EU partners within the network

The collaboration with the EU partners has been multi fold. Joint experiments at the GANIL and GSI facilities (see the short report on the WP), exchange of experimental know-how and instrumentation (the know-how about MINIBALL array; e.g. a detector specialist from K.U.Leuven has been trained at U.Köln, the plunger method to measure life times developed at U.Köln has been used in a recent experiment in the Hg isotopes in Argonne National Laboratory, the know-how on in-flight polarization with CSNSM), exchange of data and data analysis procedures (exchange of Coulomb excitation analysis procedures with U.Köln, data exchange from g-RISING at GSI with U.Köln and Coulomb excitation on Cu isotopes with CSNSM and on

the Po isotopes with GANIL) and several joined publications result from the networking with our EU partners. The added value stems from the swift and intensive exchange of all this material. This has resulted in unique opportunities for e.g. new proposals or parasitic beam time at the GANIL and GSI facilities, more effective data analysis procedures and extensive debugging of them as well as intense contacts with the theory groups present at GSI, GANIL and U.Köln. The budget from the network for the EU partners was mainly used for travel expenses and to fund post-doc positions. The EU partners have invested in the BriX program by e.g. producing delicate targets (from enriched material or very thin targets) used for BriX experiments, tailored and homemade electronic board for the Miniball detectors, consumable detector system and essential support (man power and consumables) for experimental campaigns at GSI and GANIL but also at other facilities.

B. International activities

Conferences and workshops

Apart from the IAP days, most of the workshops and schools that are mentioned under 3.1 are international activities involving organizers, speakers and/or participants outside the BriX network collaboration. Next to these international activities, staff members from the BriX network were involved in the organization of workshops e.g. at the Institute for Nuclear Theory (University of Washington, Seattle, USA) and the European Center for Theoretical Studies in Nuclear Physcis and Related Topics (ECT*, Trento, Italy).

The community of radioactive ion beam research has decided in 2009 to merge two major international conferences of our field; "International Conference on Exotic Nuclei and Atomic Masses (ENAM)' and the 'International Conference on Radioactive Nuclear Beams (RNB)'. The origin of the ENAM conferences goes back to the 1950s and 1960s to the 'Atomic Mass and Fundamental Constants (AMCO)' and the 'Nuclei Far From Stability (NFFS)' series of conferences. While the first RNB conference was organized in Berkeley, U.S.A. (1989). Both conferences were organized every three to four years since then. In order to increase the visibility of radioactive ion beam research one flagship conference series was proposed under the name of 'Advances in Radioactive Isotope Science (ARIS)'. The first one in this new series ARIS – 2011 will be held in Leuven, Belgium, from May 29 to June 3, 2011 and organized with the BriX network partners of ULB and K.U.Leuven.

Staff members of the network are member of the International Advisory Committee of several international conferences and of board of directors of international schools.

Staff members of the BriX network give colloquia and lectures at several international schools and are invited to as guest lectures at different universities. Some examples of lectures are given below:

- Theoretical nuclear physics school "Exotic Nuclei: New Challenges"
(Les Houches, France, 14-18 mai 2007)

- Ecole Joliot-Curie 2007 "Les réactions nucléaires comme sondes de la structure"
(Maubuisson, France, 19-22 septembre 2007)

- University of West Scotland, Paisley, invited lectures, 11-14 March, 2008
Quasi particle excitations in transactinide nuclei

- EP-ISOLDE Division, CERN, Geneva (Switzerland), lectures in 2007 and in 2008

- Trieste INCTP Abdus Salam (Italy) 19/5/2008 au 30/5/2008
Summer school "Joint ICTP-IAEA Workshop on Nuclear Reaction Data for Advanced Reactor Technologies"

- University of Padova and Inst. Nucl. Physics Legnaro (IT), April 16 and 17, 2009

- University of Surrey, U.K. 7/1/2009 au 9/1/2009
Mini-school on Nuclear Reaction Theories for Nuclear Astrophysics

- Rio de Janeiro, Brésil 25/1/2009 au 31/1/2009
Summer school "XIV Escola de Verão Jorge André Swieca Física Nuclear Teórica"

- Lectures at the European Summer School organized in Strasbourg: The Secrets of the Atomic Nucleus (June 28 - July 4, 2009)

- “Euroschool on Exotic Beams” September 4-11, 2009, Leuven, Belgium

- “The 8th CNS-EFES summer school” August 26 - September 1, 2009 University of Tokyo (Japan)

- Bonn-Cologne Graduate School of Physics and Astronomy, 22-26 March 2010

Experimental campaigns at international facilities
At the large scale accelerator facilities research groups of the BriX network were involved in several experiments as listed under 3.2. Furthermore members of the network are actively participating in other international collaborations like the nEDM (neutron Electric Dipole Moment) project at the Paul Scherrer Institute (PSI, Switzerland), the MINIBALL collaboration, the RISING collaboration and the COLLAPS collaboration.

Participation in EU research programs
The Brix network partners were also deeply involved in the “Integrated Infrastructure Initiative for EUROpean Nuclear Structure research (EURONS)” activity via different Joint Research Activities focuses on the development of new laser, ion trap and detection techniques and via an active participation in the transnational access program as well as the network activities. Currently negociations are undertaken with the EU for a new integrated infrastructure initiative called ENSAR. Again the BriX network is strongly involved in this activity. A Marie Curie Fellowship was obtained for an Italian post-doc was obtained to work within the network.

NuPECC Long Range Plan exercise 2010

Several staff members of the BriX network are convener of member of the working groups that prepare the new 2010 Long Range Plan for nuclear physics research in Europe.

4.3 Durability of IAP

Based on the eventual outcome of NuPECC's Long Range Plan 2010 exercise and on the possibilities offered by the new major facilities for radioactive ion beam research it is evident that challenging and interesting nuclear-physics research opportunities are present on the mid- and long term future in Europe. By selecting a limited number of challenging projects within the wide range of possibilities, the present BriX network's activities have paved the road to allow Belgian researchers to make use of the future opportunities and, in many cases, to take up a leading role. Four major new or upgraded research infrastructures are now at the horizon for future radioactive research in Europe: HIE-ISOLDE, SPES, SPIRAL-2 and FAIR and the ISOL@MYRRHA projects. HIE-ISOLDE, SPES and SPIRAL-2 prepare the road for the EURISOL project the future European Isotope Separator On Line facility. EURISOL and MYRRHA are long-term future planned. Based on the research performed during the previous IAP phases combined with Europe's future plans the following lines of research on the mid-term and long term future are currently under investigation for the next IAP phase.

- The BriX collaboration plans to continue its strong involvement in the HIE-ISOLDE project through proposals for multi-Coulomb excitation measurements, few-nucleon transfer reactions and a low-energy program using the higher intensity low-energy ISOLDE beams (the WITCH, laser- and decay-spectroscopy programs).
- The involvement in SPIRAL-2 follows two paths:
    - the development and installation of a gas cell based laser ion source for production and in-source laser spectroscopy of isotopes along the N=Z line (close to ^{100}Sn) and in the actinide region produced in heavy ion fusion evaporation reactions.
    - the contribution to the laser spectroscopy work of the so-called DESIR project making use of the high intensity beams of fission products from the SPIRAL-2 uranium target or on the longer term the beams from the S3 laser based gas cell.
- The involvement in the current GSI activities (e.g. alpha decay and BDF experiments) will be be continued and the involvement in FAIR is currently focused around laser spectroscopy in the NuSTAR program. Further involvement in the FAIR project is under discussion.
- Finally, the ISOL@MYRRHA project has been initiated by the BriX network and it is clear that on the long term this project will be the main focus of the research performed in the network.

The current partners of the BriX network wish to continue their collaborative effort in the next IAP phase. As mentioned above, an interesting and challenging scientific program can be proposed for the coming 10 years and Belgian researchers are very well placed to take up these challenges. Some changes in the network's composition are planned. At K.U.Leuven a new professor in nuclear-reaction physics has been nominated in 2010 and a new group focusing on this discipline will be established. This will definitely strengthen the network's activities. Because of the retirement of two staff members from UGent, the contribution of UGent to the network's program will be reoriented and will result in new initiatives related to nuclear theory. With the approval of the MYRRHA project, the SCK•CEN partner will increase its research activities in radioactive beam research and will take up a even larger role in the network. Next to this, first

contacts have established with the University of Liège where the atomic physics group is building an atom trap for high-precision laser spectroscopy measurements. In very interesting new direction is to use of trapped radioactive isotopes produced by the ISOL@MYRRHA facility. We are currently investigating a possible involvement of this new partner as this will give a very nice addition to the BriX port-folio of research topics. Finally, it can be expected that the approval of the MYRRHA project will create new initiatives for nuclear physics research at other Belgian universities. Under the initiative of SCK•CEN together with the present university partner in BriX, we will set-up inform rounds and possibly even trigger new developments. It is clear that we will follow these possible new initiatives very closely and, if possible, take them up in our future BriX network's activities.

5. OUTPUT

5.1 IAP publications

The 10 most relevant publications of the network's activities are listed below. The full list of publications is included in annex 1. In the period from 2007 to 2010, over 150 papers were published in refereed journals of which 38 were letters (Physical Review Letters or Physics Letters). One third of these were co-publications with co-authors from at least two partners from the BriX network involved.

Physical Review Letters 98 (2007) 112502
"Nuclear charge radii of neutron deficient lead isotopes beyond N=104 mid shell"
H. De Witte, A. N. Andreyev, N. Barre, M. Bender, T. E. Cocolios, S. Dean, D. Fedorov, V. N. Fedoseyev, L. M. Fraile, S. Franchoo, V. Hellemans, P. H. Heenen, K. Heyde, G. Huber, M. Huyse, H. Jeppessen, U. Koster, P. Kunz, S. R. Lesher, B. A. Marsh, I. Mukha, B. Roussiere, J. Sauvage, M. Seliverstov, I. Stefanescu, E. Tengborn, K. Van de Vel, J. Van de Walle, P. Van Duppen, and Yu. Volkov
This paper reports on the first experimental determination of the mean square charge radii of neutron deficient lead isotopes beyond N=104; midshell between 82 and 126. It represents the first direct experimental evidence that these lead isotopes are essentially spherical, in contrast to various speculative suggestions done in the past based on indirect experimental data. The data are very well reproduced by beyond mean field and symmetry based model descriptions. The in-source laser spectroscopy technique that was developed for this measurement has now been applied for the neutron-deficient polonium isotopes where the preliminary results show a very strong deviation from a spherical shape. These findings are essential to obtain an in-depth understanding on individual nucleon behavior and collective phenomena.

Physical Review Letters 100 *(2008)* 112502
Interplay between single-particle and collective effects in the odd-A Cu isotopes beyond N=40
Stefanescu I., Georgiev G., Balabanski D., Blasi N., Blazhev A., Bree N., Cederkaell J., Cocolios T., Davinson T., Diriken J., Eberth J., Ekstroem A., Fedorov D., Fedosseev V., Fraile L., Franchoo S., Gladnishki K., Huyse M., Ivanov O., Ivanov V., Iwanicki J., Jolie J., Konstantinopoulos T., Kroell T., Kruecken R., Koester U., Lagoyannis A., Lo Bianco G., Maierbeck P., Marsh B., Napiorkowski P., Patronis N., Pauwels D., Rainovski G., Reiter P., Riisager K., Seliverstov M., Sletten G., Van de Walle J., Van Duppen P., Voulot D., Warr N., Wenander F., Wrzosek K.
This experimental paper reports new Coulomb excitation results on odd-mass copper isotopes between N=40 and 50. This follow up paper on the Coulomb excitation on isomeric beams of the copper isotopes and on neutron-rich Zn beams, evidenced for the first time shape coexistence in the heavy Cu isotopes and clarified the single particle nature of some of the excited states in these nuclei. These data are essential to understand the evolution of the nuclear structure around ^{78}Ni. Theoretical descriptions so far failed in reproducing these data.

Physical Review Letters 103 (2009) 102501

Magnetic dipole moment of $^{57,59}Cu$ measured by in-gas-cell laser spectroscopy;
T.E. Cocolios, A.N. Andreyev, B. Bastin, N. Bree, J. Buscher, J. Elseviers, J. Gentens, M. Huyse, Yu. Kudryavtsev, D. Pauwels, T. Sonoda, P. Van den Bergh, P. Van Duppen.
This paper reports the magnetic dipole moment of ^{57}Cu, a nucleus that has one proton more compared to doubly magic ^{56}Ni. The technique of in-gas cell laser spectroscopy was developed for this measurement and thanks to its high sensitivity the measurement was possible. The new result refuted a recent measurement using an nuclear magnetic resonance technique and is in agreement with the state-of-the-art shell model calculations indicating that the ingredients to describe the nuclei around the Z=N=28 shell closure are well understood and implemented in the present models. The paper was taken up by the American Physical Society in their "Physics: spotlighting exceptional research" section.

Physical Review Letters103, 142501 (2009)
Nuclear Spins and Magnetic Moments of $^{71;73;75}Cu$: Inversion of $\pi 2p_{3/2}$ and $\pi 1f_{5/2}$ Levels in ^{75}Cu
K. T. Flanagan, P. Vingerhoets, M. Avgoulea, J. Billowes, M. L. Bissell, K. Blaum, B. Cheal, M. De Rydt, V. N. Fedosseev, D. H. Forest, Ch. Geppert, U. Ko¨ster, M. Kowalska, J. Kramer, K. L. Kratz, A. Krieger, E. Mané, B. A. Marsh, T. Materna, L. Mathieu, P. L. Molkanov, R. Neugart, G. Neyens, W. Nörtershäuser, M. D. Seliverstov, O. Serot, M. Schug M. A. Sjoedin, J. R. Stone, N. J. Stone, H. H. Stroke,G. Tungate, D. T. Yordanov, and Yu.M. Volkov
This paper reports experimental evidence for the inversion of the proton single particles states at ^{75}Cu using the collinear laser spectroscopy technique. This inversion was suggested by several model predictions as due to the tensor component in the nucleon-nucleon force but the exact location where the inversion occurs forms a key element in the understanding of the nuclear structure towards ^{78}Ni. Interesting to note is that first hints for this inversion surfaced from beta-decay studies performed in the '90's by other research groups from the present network.

Physical Review Letters 102 (2009) 142302
"Test of the Conserved Vector Current Hypothesis in T = 1/2 mirror transitions and new determination of |Vud|"
O. Naviliat-Cuncic and N. Severijns
A new method is suggested to address the Vud quark mixing matrix element. It is independent of other approaches and relies on precise determinations of the ft-values and beta decay correlations for mirror nuclei . Based on suitable data available in the literature for such nuclei a value for Vud could be extracted that has a similar precision as the value from measurements in neutron decay. Dedicated measurements of the beta asymmetry parameter for selected mirror nuclei could further significantly improve the precision, thus contributing to sensitive tests for new physics beyond the Standard Model.

Physical Review C 80 (2009) 062501
"β asymmetry parameter in the decay of 114In"
F. Wauters, I. Kraev, M. Tandecki, E. Traykov, S. Van Gorp and N. Severijns
The beta asymmetry parameter for the pure Gamow-Teller decay of 114In is reported. For this, the low-temperature nuclear orientation method was combined with a GEANT4-based simulation code allowing to address in detail, and for the first time, the effects of scattering and of the

magnetic field. The result obtained constitutes the most accurate value for the asymmetry parameter of a nuclear beta transition to date. The value is in agreement with the Standard Model prediction and provides new limits on tensor-type charged weak currents.

Physics Letters B686(2010),109

“Shell evolution and nuclear forces”

N.A.Smirnova, B. Bally, K.Heyde, F. Nowacki and K. Sieja

We present a quantitative study of the role played by different components characterizing the nucleon-nucleon interaction in the evolution of the nuclear shell structure. It is based on a spin-tensor decomposition of an effective two-body shell-model interaction and the subsequent study of effective single-particle energy variations in a series of isotopes or isotones. The technique allows us to separate unambiguously contributions of the central, vector and tensor components of the realistic effective interaction. We show that while the global variation of the single-particle energies is due to the central component of the effective interaction, the characteristic behaviour of spin-orbit partners is mainly due to its tensor part. Based on the analysis of a well-fitted realistic interaction in the sdpf shell-model space, we analyze in detail the role played by the different terms in the formation and/or disappearance of N=16, N=20 and N=28 shell gaps in neutron-rich nuclei.

SCK•CEN external report ER-115 *(2009)*

ISOL@MYRRHA: an on-line isotope separator coupled to the MYRRHA proton accelerator;

D. Pauwels, P. Schuurmans, M. Huyse, G. Neyens, R. Raabe, N. Severijns, K. Temst, P. Van Duppen Piet, A. Vantomme, H. Aït Abderrahim Hamid, P. Baeten, D. De Bruyn , J. Heyse Jan, L. Popescu, D. Vandeplassche, J. Wagemans, P.-H. Heenen, P. Descouvemont, D. Baye, J.-M. Sparenberg, K. Heyde and C. Wagemans.

This report described the physics opportunities of the ISOL@MYRRHA project, a project whereby part of the beam intensity of the MYRRHA accelerator will be used for the production of radioactive ion beams for experiments that need extremely long beam times. Interesting applications in the field of fundamental interaction studies, nuclear-, atomic- and solid-state physics and biomedicine (the production of radioisotopes) have been identified. A technical section on the expected performances of this facility is included. The report will form the road map towards the realization of ISOL@MYRRHA and is used to trigger interest from the international community. The report is added as attachment.

Report on Progress in Physics 73 (2010) 036301

P. Descouvemont, D. Baye

The R-matrix theory

An extensive review paper on the R-matrix theory was published focusing on the different facets of this important theory for scattering properties from the Schrödinger equation in general as well as for describing cross sections from nuclear reactions. In addition to elastic scattering, the R-matrix formalism is also applied to inelastic and radiative-capture reactions and more recent and more ambitious applications of the theory in nuclear physics are given.

Physics Letters B, accepted March 2010

g Factor of the 7^- isomer in ^{126}Sn and first observation of spin-alignment in relativistic fission
G. Ilie, G. Neyens, G.S. Simpson, J. Jolie, A. Blazhev, H. Grawe, R.L. Lozeva, N. Vermeulen, L. Atanasova, D.L. Balabanski, F. Becker, P. Bednarczy, C. Brandau. L. Caceres, S.K. Chamoli, J.M. Daugas, P. Doornenba, J. Gerl, M. Gorska, J. Grebosz, M. Hass, M. Ionescu-Bujor, A. Jungclaus, M. Kmiecik. M. Kojouharov, N. Kurz, A. Maj, S. Mallion, O. Perru, M. Pfutzner, Zs. Podolyak, W. Prokopowicz, M. De Rydt, T.R. Saito, H. Schaffner, K. Turzo, J. Walker, E. Werner-Malento, H.J. Wollersheim
The g-factor from a 7^- isomer in ^{126}Sn was determined using the within the collaboration developed technique of in-flight spin alignment. It represents the first measurements whereby fission of beams at relativistic energies was used. This results marks new opportunities using this production technique to measure g-factors of isomers in exotic nuclei.

5.2 Appeal of the network

The network activities have been presented at international conferences and workshops under the name of the 'BriX' network (Belgian Research Initiative on eXotic nuclei), improving the visibility of the Belgian nuclear physics community as a whole. A logo has been designed and this is used for all presentation.

5.3 PhD and postdoc training

As mentioned before under item 3.3, a large number of post-docs and PhD students that worked within the BriX network, have obtained a permanent position at a university or research institute (mainly abroad). Within the network the PhD students and post-docs get a solid training in presenting their results at the IAP-BriX days and the other workshops and schools organized by the network. Furthermore, as most experimental campaigns are executed in an international collaboration, they are confronted with their international colleagues and take active part in the daily meetings and discussions during the runs. Finally, the dedicated working meetings to discuss the status of the analysis and the joint publications form excellent training activities to prepare in-depth discussions and to formulate critical views. The international visibility of the research performed within BriX and the numerous international contacts of the staff members of the network creates a doorway for the PhD students and post-doc towards applying for research positions elsewhere.

PhD students and post-docs that worked within the BriX network

The IAP funding was used for 6.5 positions for PhD students and 10 post-doc positions, while the institutes contributed with 27 positions for PhD students and 20 post-doc positions.

- Supported by the IAP funding
PhD students
K.U.Leuven: G. Soti, A. Smolkowska, C. Petermann, L. Pinto de Almeida Amorim
ULB: E. Pinilla, T. Druet (50%)
UGent: S.Vermote

Post-doc:

K.U.Leuven: Andreev Andrei, Darby Iain, Seliverstov Maxim, Roger Thomas, Breitenfeldt Martin, Rajabali Mustafa
ULB: V. Hellemans
UGent: S.Vermote, S. De Baerdemacker
SCK•CEN: L. Popescu

- Not supported by the IAP funding
PhD students
K.U.Leuven: Bree Nick, Büscher Jeroen, Cocolios Thomas Elias, Diriken Jan, Elseviers Jytte, Ivanov Oleg, Pauwels Dieter, Radulov Deyan, Van de Walle Jarno, Kozlov Valentin, Coeck Sam, De Leebeeck Véronique, Kraev Il'ya, Tandecki Michaël, Van Gorp Simon, Wauters Frederik, De Rydt Marieke, Vermeulen Nele, Vingerhoets Pieter, Yordanov Deyan Todorov
ULB: M. Theeten, A. Damman, J. Dohet-Erhaly, A. Pupasov
UGent: V.Hellemans, S. De Baerdemacker, K. Van Houcke

Post-doc:
K.U.Leuven: Bastin Beyhan, Koudriavstev Iouri, Patronis Nikolaos, Stefanescu Irina Stefania, Venhart Martin, Raabe Riccardo, Passini Matteo, Ivanov Oleg, Pauwels Dieter, Sawicka Maria, Roccia Stéphanie, Traykov Emil (Kostadinov), Wauters Frederik, Avgoulea Tania (Malamatenia), Bissell Mark, Flanagan Kieran, Lozeva Lozeva Radomira
ULB: R. Chatterjee, P. Capel
UGent: S. De Baerdemacker, K. Van Houcke

PhD thesis (2007 – 2010)

Sam Coeck (2007, K.U.Leuven),´" Search for non Standard Model physics in nuclear beta decay with the WITCH experiment."

Veerle Hellemans (2007, UGent), ``Shape coexistence and critical phenomena in atomic nuclei''

Stijn De Baerdemacker (2007, UGent), ``The geometrical Bohr-Mottelson model: analytic solutions and an algebraic Cartan-Weyl perspective''

G. Goldstein (2007,ULB), "Etude de la dissociation de noyaux à halo par résolution numérique de l'équation de Schrödinger dépendant du temps

Kris Van Houcke (2007, UGent), ``Pairing in many-body systems: a quantum Monte Carlo approach and applications''

Deyan Yordanov (2007, K.U. Leuven), "From 27Mg to 33Mg: transition to the Island of Inversion"

Oleg V. Ivanov (2007, K.U.Leuven), "Decay of 66-Fe studied with a new beta-gamma detection setup at LISOL"

Dieter Pauwels, (2009, K.U.Leuven) "Nuclear structure around Z=28 and N=40 investigated by the beta decay of Fe, Co and Ni isotopes"

Frederik Wauters (2009, K.U.leuven), "Search for tensor type weak currents by measuring the beta asymmetry parameter in nuclear decays."

Sofie Vermote (2009, UGent), “Characteristics of light charged particle emission in spontaneous and neutron induced fission of Cm and Cf isotopes”

M. Theeten (2009, ULB), "Semi-microscopic and microscopic three-body models of nuclei and hypernuclei/Modèles semi-microscopiques et microscopiques à trois corps de noyaux et d'hypernoyaux"

Nele Vermeulen (2009, K.U. Leuven), “Quadrupole moments of isomers produced inprojectile-fragmentation reactions”

Marieke Derydt (2010, K.U. Leuven), “A dedicated b-NMR/b-NQR setup for LISE-GANIL and study of the nuclear moments of the neutron-rich Al and Cl isotopes”

Thomas Elias Cocolios (2010, K.U.Leuven) “Single-particle and collective properties around closed shells probed by in-source laser spectroscopy”

5.4 Young emerging research teams

A new professor in nuclear reaction studies has been nominated in 2010 at K.U.Leuven. He will set up a new research group and plans a program tailored to activities around the HIE-ISOLDE and GANIL facilities for the study of nuclear reactions using exotic nuclei. This new experimental group will be involved in the development of an active gas target as well as in the design and construction of a new separator/spectrometer for HIE-ISOLDE. The group will be fully inbedded in the BriX network. This new route is a very important addition to the BriX program and will definitely increase our visibility in the international community.

6. ANNEXES

Annex 1:

a. List of publications for every partner separately

(excluding the co-publications that involve different institutes from the network)

K.U.Leuven

Nuclear Instruments and Methods in Physics Research A604 *(2009)* 563-567;
Performance of silicon PIN photodiodes at low temperatures and in high magnetic fields;
F. Wauters, I.S. Kraev, M. Tandecki, E. Traykov, S. Van Gorp, D. Zákoucký and N. Severijns.

Physical Review Letters 102 *(2009)* 142302 (4 pages);
Test of the Conserved Vector Current Hypothesis in T = 1/2 mirror transitions and new determination of **|***Vud***|***;*
O. Naviliat-Cuncic and N. Severijns.

Nuclear Instruments and Methods in Physics Research A 609 *(2009)* 156-164;
A GEANT4 Monte-Carlo Simulation Code for precision β spectroscopy;
F. Wauters, I. Kraev, D. Zákoucký, M. Beck, V.V. Golovko, V.Yu. Kozlov, T. Phalet, M. Tandecki, E. Traykov, S. Van Gorp and N. Severijns.

Physical Review C 80 *(2009)* 062501 (5 pages);
β asymmetry parameter in the decay of ^{114}In;
F. Wauters, I. Kraev, M. Tandecki, E. Traykov, S. Van Gorp and N. Severijns.

European Physical Journal A 42 *(2009)* 327-331;
|V_{ud}**|** *from T=1/2 mirror transitions and the role of atom and ion traps;*
O. Naviliat-Cuncic and N. Severijns.

Physical Review C 79 9 *(2009)* 064322 (6 pages);
Hyperine field of einsteinium in iron and nuclear magnetic moment of 254Es;
N. Severijns, A.A. Belyaev, A.L. Erzinkyan, P.-D. Eversheim, V.T. Filimonov, V.V. Golovko, G.M. Gurevich, P. Herzog, I.S. Kraev, A.A. Lukhanin, V.I. Noga, V.P. Parfenova, T. Phalet, A.V. Rusakov, M. Tandecki, Yu.G. Toporov, C. Tramm, E. Traykov, S. Van Gorp, V.N. Vyachin, F. Wauters, D. Zákoucký and E. Zotov.

Physical Review Letters 102 *(2009)* 172301 (4 pages);
Measurement of the Transverse Polarization of Electrons Emitted in the Decay of a Free Neutron;
A. Kozela, G. Ban, A. Bialek, K. Bodek, P. Gorel, K. Kirch, St. Kistryn, M. Kuzniak, O. Naviliat-Cuncic, J. Pulut, N. Severijns, E. Stephan, and J. Zejma.

Nuclear Physics A 827 *(2009)* 422c-424c;
Search for Exotic Couplings in Neutron Decay: A Measurement of the Transverse Polarization of Electrons;
G. Ban, A. Bialek, K. Bodek, J. Bozek, J.P. Gorel, K. Kirch, St. Kistryn, A. Kozela, M. Kuzniak, O. Naviliat-Cuncic, N. Severijns, E. Stephan, and J. Zejma.

Nuclear Instruments and Methods in Physics Research A 611 *(2009)* 198-202;
Measurement of the Transverse Polarization of Electrons Emitted in Neutron Decay: A Search for Weak Exotic Couplings;
G. Ban, A. Bialek, K. Bodek, J. Bozek, P. Gorel, K. Kirch, St. Kistryn, A. Kozela, M. Kuzniak, O. Naviliat-Cuncic, J. Pulut, N. Severijns, E. Stephan f and J. Zejma.

Nuclear Instruments and Methods in Physics Research A 611 *(2009)* 141-143;
Additional Results from the First Dedicated Search for Neutron - Mirror-Neutron Oscillations;
K. Bodek, St. Kistryn, M. Kuzniak, J. Zejma, M. Burghoff, S. Knappe-Grüneberg, T. Sander-Thoemmes, A. Schnabel, L. Trahms, G. Ban, T. Lefort, O. Naviliat-Cuncic, N. Khomutov, P. Knowles, A.S. Pazgalev, A.Weis, G. Rogel, G. Quéméner, D. Rebreyend, S. Roccia, G. Bison, N. Severijns, K. Eberhardt, G. Hampel, W. Heil, J.V. Kratz, T. Lauer, C. Plonka-Spehr, Yu. Sobolev, N. Wiehl, I. Altarev, P.Fierlinger, E. Gutsmiedl, S. Paul, R. Stoepler, M. Daum, R. Henneck, K. Kirch, A. Knecht, B. Lauss, A. Mtchedlishvili, G. Petzoldt and G. Zsigmond.

Nuclear Instruments and Methods in Physics Research A 611 *(2009)* 133-138;
Towards a new measurement of the neutron electric dipole moment;
I. Altarev, G. Ban, G. Bison, K. Bodek, M. Burghoff, M. Cvijovic, M. Daum, P.Fierlinger, E. Gutsmiedl, G. Hampel, W. Heil, R. Henneck, M. Horras, N.Khomutov, K. Kirch, S. Kistryn, S. Knappe-Gruneberg, A. Knecht, P. Knowles, A. Kozela, J. Kratz, F. Kuchler, M. Kuzniak, T. Lauer, B. Lauss, T. Lefort, A. Mtchedlishvili, O. Naviliat-Cuncic, S. Paul, A. Pazgalev, G. Petzoldt, E. Pierre, C.Plonka-Spehr, G. Quemener, D. Rebreyend, S. Roccia, G. Rogel, T. Sander-Thoemmes, A. Schnabel, N. Severijns, Y. Sobolev, R. Stoepler, L. Trahms, A. Weis, N. Wiehl, J. Zejma, G. Zsigmond.

Physical Review D 80 *(2009)* 032003 (5 pages);
Neutron to mirror-neutron oscillations in the presence of mirror magnetic fields;
I. Altarev, C. Baker, G. Ban, K. Bodek, M. Daum, P.Fierlinger, P. Geltenbort, K.Green, M. van der Grinten, E. Gutsmiedl, P. Harris, R. Henneck, M. Horras, P.Iajdjiev, S. Ivanov, N. Khomutov, K. Kirch, S. Kistryn, A. Knecht, P. Knowles, A.Kozela, F. Kuchler, M. Kuzniak, T. Lauer, B. Lauss, T. Lefort, A. Mtchedlishvili, O. Naviliat-Cuncic, S. Paul, A. Pazgalev, J. Pendlebury, G.Petzoldt, E. Pierre, C.Plonka-Spehr, G. Quemener, D. Rebreyend, S. Roccia, G. Rogel, N. Severijns, D. Shiers, Y. Sobolev, R. Stoepler, A. Weis, J. Zejma, J. Zenner, G. Zsigmond.

Physical Review Letters 103 *(2009)* 081602 (4 pages);
Test of Lorentz Invariance with Spin Precession of Ultracold Neutrons;

I. Altarev, C. Baker, G. Ban, G. Bison, K. Bodek, M. Daum, P.Fierlinger, P.Geltenbort, K.Green, M. van der Grinten, E. Gutsmiedl, P. Harris, W. Heil, R.Henneck, M. Horras, P.Iajdjiev, S. Ivanov, N. Khomutov, K. Kirch, S. Kistryn, A.Knecht, P. Knowles, A.Kozela, F. Kuchler, M. Kuzniak, T. Lauer, B. Lauss, T.Lefort, A. Mtchedlishvili, O. Naviliat-Cuncic, A. Pazgalev, J. Pendlebury, G.Petzoldt, E. Pierre, C.Plonka-Spehr, G. Quemener, D. Rebreyend, S. Roccia, G.Rogel, N. Severijns, D. Shiers, Y. Sobolev, R. Stoepler, A. Weis, J. Zejma, J.Zenner, G. Zsigmond.

European Physical Journal A 39 *(2009)* 33;
Nuclear structure of ^{189}Tl states studied via □+/EC decay and laser spectroscopy of $^{189m+g}$Pb;
J. Sauvage, J. Genevey, B. Roussiere, S. Franchoo, A.N. Andreyev, N. Barre, J.-F. Clavelin, H. De Witte, D.V. Fedorov, V.N. Fedoseyev, L.M. Fraile, X. Grave, G. Huber, M. Huyse, H.B. Jeppesen, U. Koster, P. Kunz, S.R. Lesher, B.A. Marsh, I. Mukha, J. Oms, M. Seliverstov, I. Stefanescu, K. Van de Vel, J. Van de Walle, P. Van Duppen, and Yu.M. Volkov.

European Physical Journal 41 *(2009)* 315;
Charge radii and magnetic moments of odd-A $^{183–189}$Pb isotopes;
M.D. Seliverstov, A.N. Andreyev, N. Barre, A.E. Barzakh, S. Dean, H. De Witte, D.V. Fedorov, V.N. Fedoseyev, L.M. Fraile, S. Franchoo, J. Genevey, G. Huber, M. Huyse, U. Koster, P. Kunz, S.R. Lesher, B.A. Marsh, I. Mukha, B. Roussiere, J. Sauvage, I. Stefanescu, K. Van de Vel, P. Van Duppen, Yu.M. Volkov.

Nuclear Instruments and Methods in Physics Research B267 *(2009)* 2908;
Dual chamber laser ion source at LISOL;
Yu. Kudryavtsev, T.E. Cocolios, J. Gentens, M. Huyse, O. Ivanov, D. Pauwels, T. Sonoda, P. Van den Bergh, P. Van Duppen.

Nuclear Instruments and Methods in Physics Research B267 *(2009)* 2918;
The Laser Ion Source Trap (LIST) coupled to a gas cell;
T. Sonoda, T.E. Cocolios, J. Gentens, M. Huyse, O. Ivanov, Yu. Kudryavtsev, D. Pauwels, P. Van den Bergh, P. Van Duppen.

Physical Review C79 *(2009)* 044309;
Structure of ^{65,67}Co studied through the β decay of ^{65,67}Fe and a deep-inelastic reaction;
D. Pauwels, O. Ivanov, N. Bree, J. Buscher, T.E. Cocolios, M. Huyse, Yu. Kudryavtsev, R. Raabe, M. Sawicka, J. Van de Walle, P. Van Duppen, A. Korgul, I. Stefanescu, A.A. Hecht, N. Hoteling, A. Wohr, W.B. Walters, R. Broda, B. Fornal, W. Krolas, T. Pawlat, J. Wrzesinski, M.P. Carpenter, R.V.F. Janssens, T. Lauritsen, D. Seweryniak, S. Zhu, J.R. Stone, X. Wang.

Physical Review C 79 *(2009)* 044325;
Evidence for a β-decaying 1/2^{-} isomer in ^{71}Ni;
I. Stefanescu, D. Pauwels, N. Bree, T.E. Cocolios, J. Diriken, S. Franchoo, M. Huyse, O. Ivanov, Yu. Kudryavtsev, N. Patronis, J. Van De Walle, P. Van Duppen, and W.B. Walters.

Physical Review C 79 *(2009)* 054613;
Fission barriers for Po nuclei produced in complete fusion reactions with heavy ions; R.N. Sagaidak, A.N. Andreyev.

Physical Review C 80 *(2009)* 031303(R);
Evidence for prolate structure in light Pb isotopes from in-beam γ-ray spectroscopy of ^{185}Pb;
J. Pakarinen, A.N. Andreyev, R. Julin, S. Juutinen, S. Antalic, L. Bianco, I.G. Darby, S. Eeckhaudt, T. Grahn, P.T. Greenlees, D.G. Jenkins, P. Jones, P. Joshi, H. Kettunen, M. Leino, A.-P. Leppanen, P. Nieminen, M. Nyman, R.D. Page, J. Perkowski, P.M. Raddon, P. Rahkila, D. Rostron, J. Saren, C. Scholey, J. Sorri, B. Streicher, J. Uusitalo, K. Van de Vel, M. Venhart, R. Wadsworth, D.R. Wiseman.

Physical Review C 80 *(2009)* 034307;
β-decay study of ^{77}Cu;
N. Patronis, H. De Witte, M. Gorska, M. Huyse, K. Kruglov, D. Pauwels, K. Van de Vel, P. Van Duppen, J. Van Roosbroeck, J.-C. Thomas, S. Franchoo, J. Cederkall, V.N. Fedoseyev, H. Fynbo, U. Georg, O. Jonsson, U. Koster, T. Materna, L. Mathieu, O. Serot, L. Weissman, W.F. Mueller, V.I. Mishin, D. Fedorov.

Physical Review C 80 *(2009)* 054304;
β decay of the $\pi f_{5/2}$ ground state of ^{77}Cu studied with 225 MeV and 0.2 MeV purified radioactive beams;
S.V. Ilyushkin, J.A. Winger, C.J. Gross, K.P. Rykaczewski, J.C. Batchelder, L. Cartegni, I.G. Darby, C. Goodin, R. Grzywacz, J.H. Hamilton, A. Korgul, W. Krolas, S.N. Liddick, C. Mazzocchi, S. Padgett, A. Piechaczek, M.M. Rajabali, D. Shapira, E.F. Zganjar.

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